# The Exchanges of Fresh and Salt Waters in the Bay of Fundy and in Passamaquoddy Bay[1]


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ABSTRACT

The results of 385 previously published hydrographic stations in the Bay of Fundy are summarized, and the average distribution of salinity at various depths is derived from these data.

The total quantity of river water accumulated within the Bay of Fundy is equivalent to the quantity introduced by the rivers during a period of about 76 days.

The exchange ratios for tidal excursion segments of the Bay of Fundy range from 0.17 in the neighborhood of Cape Chignecto to 0.056 in the segment immediately south of Grand Manan. In the upper tidal reaches of the Petitcodiac River and of Minas Basin the exchange ratios are about 0.95.

The estuary of the St. Croix River has been studied and calculations indicate that about 15 tides, or 8 days are required on the average to replace one day's river flow. The exchange ration in this case range from 0.905 to 0.30.

From a summary of existing data in Passamaquoddy Bay it is calculated that the total accumulation of river water is equal to the quantity introduced by the rivers in a period of about 16 days.


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## INTRODUCTION

The great tides of the Bay of Fundy, and the enormous effect they have in mixing the river effluents to considerable depths in the area, have been emphasized by all hydrographers who have studied the Bay. It seemed desirable to determine whether the techniques for evaluating the circulation in estuaries, which have been developed for much smaller and generally shoaler regions, would be applicable to the Bay of Fundy.

The Bay of Fundy, shown in Figure 1, is a narrow, funnel-shaped arm of the Gulf of Maine, varying in width from about 40 miles at Grand Manan, to about

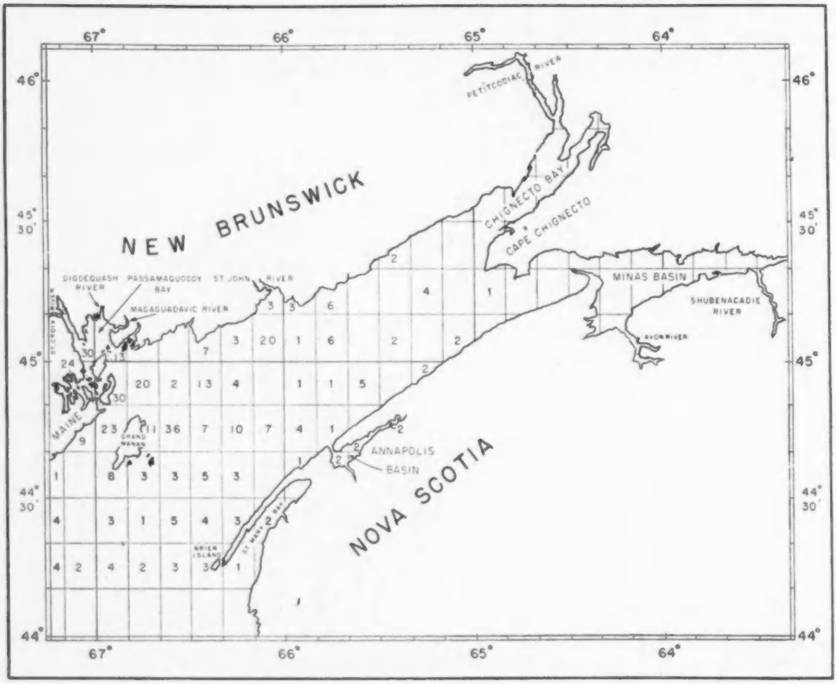


FIGURE 1. The Bay of Fundy. The numbers in the ten-minute squares show the number of stations available.

25 miles at Cape Chignecto. The maximum depth decreases, over this same distance, from about 116 fathoms to about 25 fathoms. Above Cape Chignecto the Bay subdivides into two arms, Chignecto Bay and Minas Basin.

The general pattern of circulation of the surface waters of the Bay of Fundy has been described by Mavor (1922, 1923), Hachey (1931) and Watson (1936).

The transport of drift bottles has confirmed the pattern deduced from the distribution of density. The results show a counterclockwise circulation, with more saline water occupying the southern part and flowing into the Bay along the Nova Scotia shore. Fresher water occupies the northern part and flows seaward along the New Brunswick shore and south of Grand Manan. The drift bottles released close to the Nova Scotia shore were generally picked up to the east of the point of release. The bottles released farther than 5 to 10 miles from the Nova Scotia shore usually drifted northward and were recovered in New Brunswick. These results indicated that some water transport across the Bay occurs throughout its length. Many of the drift bottles released by Bigelow (1927) and by Fish and Johnson (1937) in the Gulf of Maine were found in the Bay of Fundy, predominantly along the Nova Scotia shore. These results confirm the inflow of water along this shore and establish the source of this surface water as, in part at least, an offshoot of the Gulf of Maine eddy. Some contribution of surface water from the Scotian Shelf may also occur and Mavor (1922) mentions this as the source of the high salinity inflow. Bigelow (1927, p. 832), however, concludes that the Nova Scotian current flows into the Gulf of Maine in volume during only a few weeks in spring.

The circulation around Grand Manan is less firmly established. Both Mavor and Watson concluded that there was a clockwise circulation around Grand Manan, though the latter commented that it was small. Fish and Johnson (1937) released 24 drift bottles between West Quoddy Head and Whale Cove, Grand Manan. Of the eight recovered, five drifted to the north or east of the point of release, three drifted southwest to the coast of Maine. Although they drew probable lines of drift in a clockwise direction around Grand Manan, their results are subject to other interpretations. McLellan (1951) concludes from hydrographic data that there is no conclusive evidence of residual currents in Grand Manan Channel, though MacGregor and McLellan (1951) observed net southward movements a couple of weeks later. Their observed drift would indicate a counterclockwise circulation around Grand Manan. They suggest that the residual current may be variable depending upon meteorological conditions.

The deep water in the Bay of Fundy has a relatively high salinity (32.5 to $> 33\ ^0/_{00}$) and is derived from the deep water in the Gulf of Maine. Bigelow (1927) showed that, at depths of 100 meters, water of salinity greater than $33\ ^0/_{00}$ and moderately high temperature (4–5°C.) was continuous with similar water in the Gulf of Maine. Watson (1936) observed that the salinity of the water at 100 meters off Grand Manan increased from $32.5\ ^0/_{00}$ at the end of April to $33.2\ ^0/_{00}$ in September. He concluded that there must be a "steady inflow of salt deep water from the Gulf of Maine which more than compensates for the dilution from vertical mixing".

The river effluents entering the Bay of Fundy are derived from seven main drainage basins, which are illustrated by Watson (1936) who gives mean monthly rates of flow for each. The drainage into Chignecto Bay comprises about 9 per cent and that into Minas Basin about 15 per cent of the total mean annual flow. The fresh water entering at the head of the Bay of Fundy is thus only about one-

quarter of the total river drainage. Most of the remainder (60 per cent) is contributed by the St. John River, which enters the New Brunswick side of the Bay about midway between Cape Chignecto and Grand Manan. Both Hachey (1935) and Watson (1936) show that the diluted water issuing from the mouth of the St. John estuary extends southward for 40 to 50 miles and is identifiable at the surface east of Grand Manan. The St. John water, by the time it has reached this degree of extension, has a salinity of 31.5 ‰, which, as Hachey (1935) calculates, shows an admixture of about 64 times its own volume of sea water (of salinity 32.0 ‰). This large volume of sea water, which at the time of spring freshet in 1932, was greater than four million cubic feet per second, must be provided by an inflow of sea water, either below the diluted surface water or to the east of it.

The presence of the large effluent from the St. John along the north shore, and the necessarily enormous counter-flow of sea water, must contribute in a substantial way to the development and maintenance of the seaward-directed current of diluted water along this shore, and to the general counterclockwise circulation of the Bay.

The tidal wave is augmented within the Bay of Fundy so that the mean range increases from about 14 feet at Brier Island to nearly 40 feet in the inner end of Minas Basin, (Dawson, 1917). Along the south shore of the Bay the mean range of tides is somewhat greater than it is along the north shore (Marmer, 1926; Redfield, 1950). This Kelvin wave effect would augment the tendency for the waters to circulate in a counterclockwise direction.

The available data do not give conclusive evidence concerning the rate of the circulation within the Bay of Fundy. Hachey (1934) has deduced, from the temperature distribution, that the rate of replacement of Bay of Fundy waters differs from year to year. The differences are correlated with the prevailing winds and with variations in the discharge of the St. John River. His data, however, do not lend themselves to direct computations of velocity. Watson (1936) concluded that the St. John River effluent had a net seaward drift of 34 cm./sec. (0.7 knots). Mavor (1922) derived non-tidal drifts of 2.34 to 6.53 miles per tidal cycle (0.19 to 0.52 knots), from Dawson's (1908) current measurements. Mavor also obtained, from drift bottle returns, net drifts ranging from 4 to 5 miles per day (0.17 to 0.21 knots).

The objective of this investigation was to determine, from available data, the distribution of river water within the Bay of Fundy and Passamaquoddy Bay, and to evaluate the rate of its transport by the methods used by Tully, 1949; Ketchum, 1950; Ketchum, Redfield and Ayers, 1951. The empirical calculations of exchange ratios and of total accumulation of river water by the method described by Ketchum (1951) have also been made, and the results compared with those obtained from the observed distribution of salinity.

It should be emphasized that the conclusions drawn in this paper represent average distributions and average exchanges of water across complete cross-sections of the Bay. The foregoing summary of the circulation should make it clear that the actual conditions in various parts of the cross-sections will vary considerably from these averages.

## THE BAY OF FUNDY

The salinity results of 385 hydrographic stations have been obtained from the published literature referred to in the introduction and from the files of oceanographic data at the Woods Hole Oceanographic Institution. These data have been summarized by grouping the results within ten-minute squares, and the number of observations in each such square in the area studied is indicated in Figure 1. Data are available over the major part of the Bay. They are sparse in the northeastern area, and no salinity information has been found for Chignecto Bay and Minas Basin.

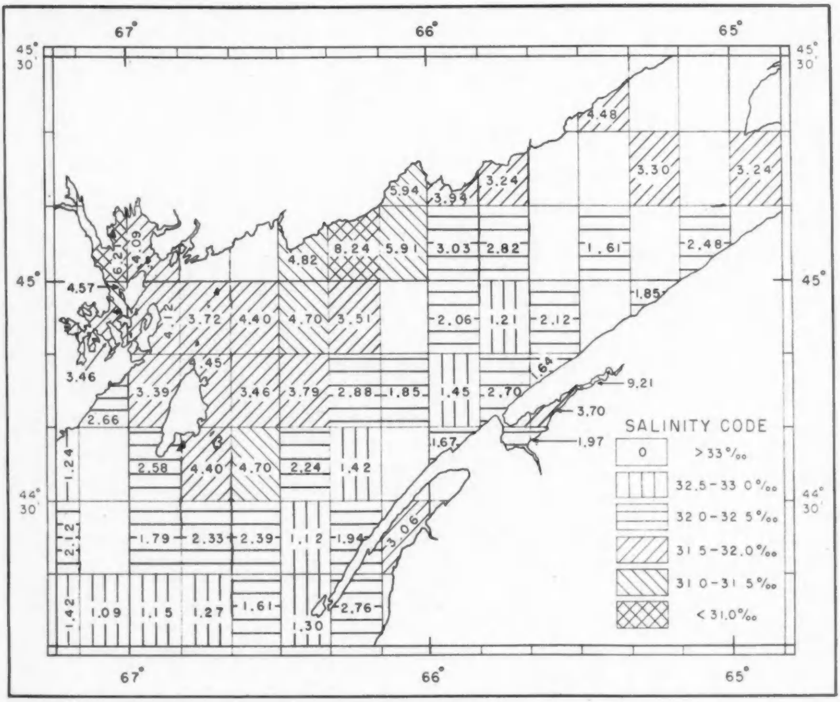


FIGURE 2. The distribution of average salinity and river water, 0–25 meters.

### OBSERVED DISTRIBUTION

#### SALINITY

In each ten-minute square average salinities, weighted for depth of observations, have been computed for depth ranges of 0 to 25, 25 to 50, 50 to 100, and greater than 100 meters. The results are given in Figures 2, 3, 4, and 5, where the salinity range is shown by the hatching pattern, and the percentage of fresh water is given by the number in each square. In the upper 25 meters (Figure 2) water with a salinity greater than 32 ‰ predominates throughout the southern

part of the Bay along the Nova Scotian shore except for the stations directly opposite Minas Basin where the observed salinity was slightly less than 32 ‰. In contrast, the water throughout the northern part of the Bay has a salinity lower than 32 ‰. The greatly freshened water resulting from the admixture of the St. John River outflow extends to the southwest, from St. John Harbor as far as the shoals in the neighborhood of Grand Manan. Average fresh-water contents greater than 4 per cent (salinities < 31.7 ‰) are thus found more than 50 miles from the mouth of the St. John River. It is clear that these average values faithfully reflect the counterclockwise circulation previously described and

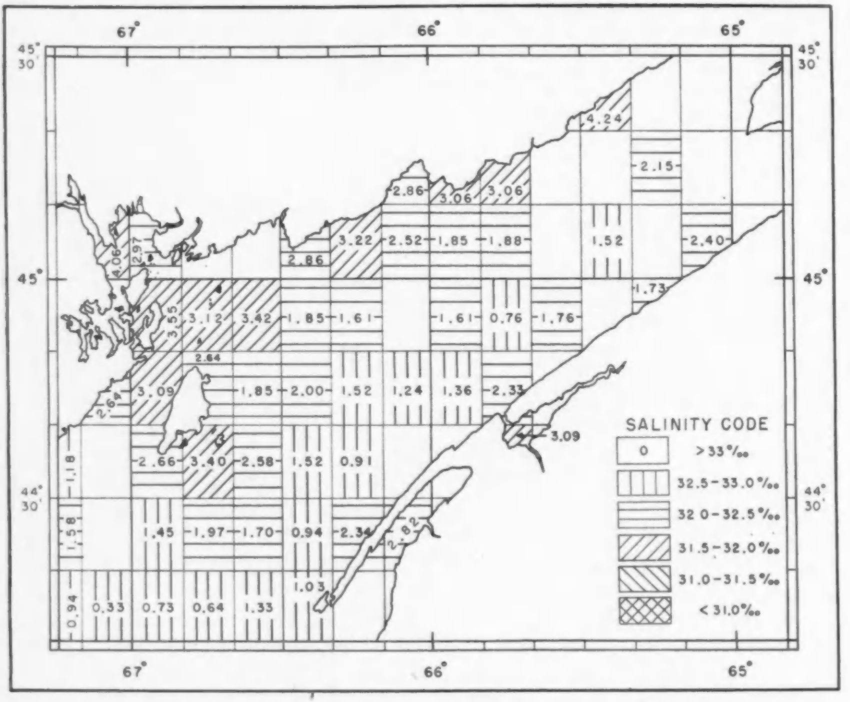


FIGURE 3. The distribution of average salinity and river water, 25–50 meters.

summarized in the introduction. It is of some interest that the surface water to the west of Grand Manan Island is fresher than the surface water to the southward. This indicates that some river water from either the St. John or from Passamaquoddy Bay is present. This observation does not confirm the clockwise circulation around Grand Manan that has been previously reported.

The mean distribution of salinity between 25 and 50 meters is generally similar to that of the surface water except that the water is more saline throughout the Bay. The freshest water is found along the New Brunswick shore, both

to the east and west of the St. John River. Directly opposite the St. John, however, more saline water is found—as though an indraft of high-salinity water occurred in this location. Other areas, with higher salinity than in any of the surrounding water at these depths, are found east of Grand Manan and in the northern part of Passamaquoddy Bay.

Between 50 and 100 meters the increase in salinity is even more marked, but the pattern of fresher water throughout the northern part of the Bay is maintained. Only a small part of the Bay contains water at depths greater than 100 meters, and all of this water has a salinity greater than 32.5 $^0/_{00}$.

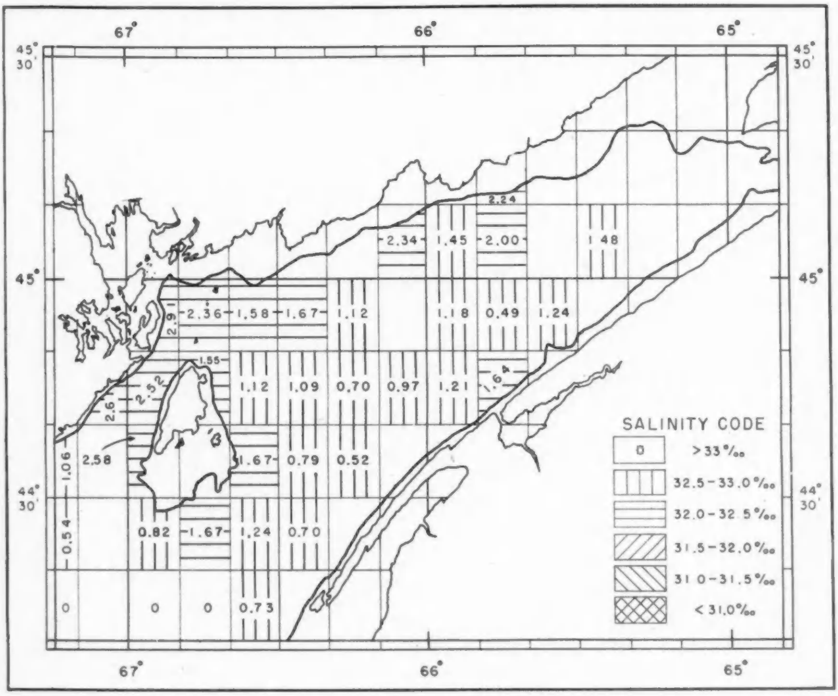


FIGURE 4. The distribution of average salinity and river water, 50–100 meters.

FRESH WATER

From the average-salinity data the proportion of fresh water in each sample has been calculated, using 33 $^0/_{00}$ as the salinity of the source sea water. Water of this salinity is found only at depths of 100 meters or more near the mouth of the Bay. Bigelow's results indicate that this salinity is characteristic of the tongue of water penetrating at these depths from the Gulf of Maine. In all of Watson's sections across the mouth of the Bay, water of this salinity appeared. The percentage of fresh water in each ten-minute square for various depths is also shown in Figures 2 to 5.

In order to compute transport from the distribution of fresh water, complete cross-sections must be used. The Bay was therefore subdivided by sections running southeast to northwest, located 11.5 miles apart. The lines thus form diagonals of some of the ten-minute squares, but a row of complete squares is included between each pair of lines. The average salinity for various depths of each segment was computed from the data previously described, and the average proportion of fresh water computed for each of the segments. The total volume and the volume to various depths was obtained by planimetering the areas between depth contours on charts Nos. 0609 and 0610 of the U.S. Navy Hydro-

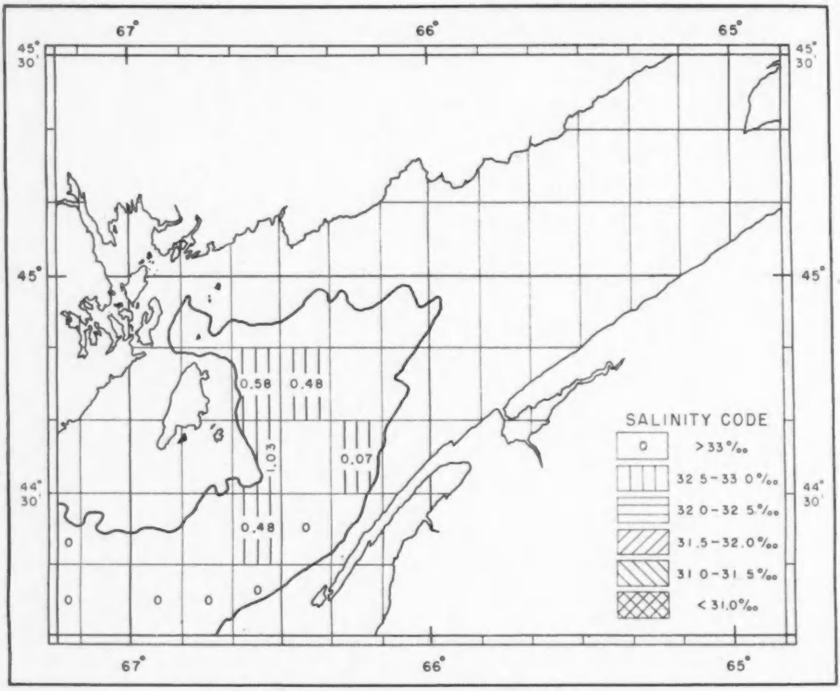


FIGURE 5. The distribution of average salinity and river water, > 100 meters.

graphic Office. From these data the proportion and total volume of fresh water within the Bay have been computed and the results are given in Table I. In Figure 6 the proportions and the accumulated volumes of fresh water are shown for various distances from Cape Chignecto.

The water is diluted with river effluents to depths of 100 meters. A small amount of fresh water is found even at greater depths. The upper 25 meters contains about half of the total fresh water in the Bay, although its volume is only 29 per cent of the total. The percentage of fresh water in the surface decreases

gradually from the neighborhood of Cape Chignecto until the freshening effect of the St. John River appears, where it increases greatly. The fresh-water content then gradually decreases again throughout the remainder of the length of the Bay. It is of interest that the percentage of fresh water in the total volume of water in each segment does not vary greatly, ranging from 2.64 per cent at Cape Chignecto

TABLE I The mean salinities, volumes of river water and flushing times for the various segments of the Bay of Fundy.

| Segment | Depth | Total volume | Mean salinity | River water | River water | Mean flushing time |
|---|---|---|---|---|---|---|
| | | $10^9 ft.^3$ | ‰ | % | $10^9 ft.^3$ | *days* |
| A | 0–25 | 860 | 32.00 | 3.03 | 26.0 | 4.98 |
| | 25–50 | 586 | 32.22 | 2.36 | 13.4 | |
| B | 0–25 | 873 | 32.094 | 2.75 | 24.0 | |
| | 25–50 | 759 | 32.206 | 2.41 | 18.3 | 5.59 |
| | 50–100 | 130 | 32.51 | 1.49 | 1.9 | |
| C | 0–25 | 949 | 32.23 | 2.32 | 22.0 | |
| | 25–50 | 851 | 32.34 | 1.99 | 16.95 | 5.75 |
| | 50–100 | 373 | 32.43 | 1.74 | 6.5 | |
| D | 0–25 | 1,069 | 31.965 | 3.14 | 33.6 | |
| | 25–50 | 982 | 32.317 | 2.07 | 20.3 | 8.51 |
| | 50–100 | 900 | 32.51 | 1.48 | 13.3 | |
| E[a] | 0–25 | 1,225 | 31.82 | 3.58 | 44.1 | |
| | 25–50 | 1,132 | 32.323 | 2.05 | 23.2 | 11.3 |
| | 50–100 | 1,540 | 32.535 | 1.41 | 21.7 | |
| F | 0–25 | 1,398 | 31.94 | 3.20 | 44.7 | |
| | 25–50 | 1,265 | 32.37 | 1.92 | 24.3 | 11.8 |
| | 50–100 | 2,044 | 32.64 | 1.09 | 22.3 | |
| | > 100 | 689 | 32.895 | 0.32 | 2.2 | |
| G[b] | 0–25 | 1,540 | 31.94 | 3.20 | 49.4 | |
| | 25–50 | 1,382 | 32.25 | 2.28 | 31.4 | 15.5 |
| | 50–100 | 2,446 | 32.53 | 1.43 | 35.0 | |
| | > 100 | 2,084 | 32.90 | 0.30 | 6.25 | |
| H[c] | 0–25 | 1,486 | 32.09 | 2.77 | 41.1 | |
| | 25–50 | 1,238 | 32.296 | 3.13 | 26.4 | 12.6 |
| | 50–100 | 1,762 | 32.435 | 1.71 | 30.1 | |
| | > 100 | 1,474 | 32.965 | 0.11 | 1.62 | |
| Total | | 31,037 | | | 600.02 | 76.03 |

a Annapolis Basin included.
b Northern part of Passamaquoddy Bay included.
c Southern part of Passamaquoddy Bay included.

to 1.66 per cent south of Grand Manan. The freshening effect of the St. John River is observable at all depths of the water column opposite its entrance (segments D and E, Table I).

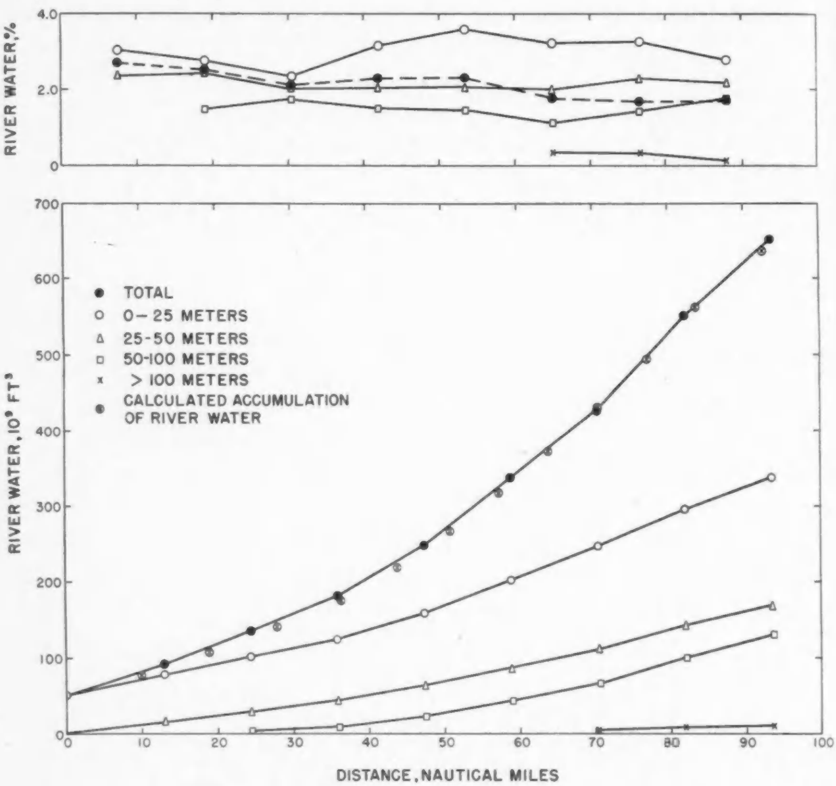


FIGURE 6. *Upper figure:* The proportions of river water at various depths, plotted at increasing distances from Cape Chignecto. *Lower figure:* The total volume of river water enclosed.

THE FLUSHING TIME

The average length of time required to remove one day's contribution of river water is defined by the ratio of the quantity of river water accumulated within the estuary to the quantity introduced daily by the rivers, and has been called the "flushing time". The average river flow for the months of April, May, June, and July, as given by Watson (1936) has been used in the computation. This period was selected because 76 per cent of the data used—293 of the 385 stations—was obtained during the period June to September. The river-flow data for the earlier months were included in the average because of the time interval

required to traverse the Bay. During this period the rivers contribute $7.9 \times 10^9 ft.^3$ per day, or $4.08 \times 10^9 ft.^3$ per tidal cycle.

The corresponding times are included in Table I, and indicate that about 76 days are required to exchange the average particle of river water in the area. Since the part of the Bay considered is about 93 miles long these results give an overall average rate of transport of about 1.22 nautical miles per day. For the various segments the rate of transport ranges from 2.3 miles per day at Cape Chignecto to 0.74 miles per day near Grand Manan. These values are, of course, somewhat less than those quoted above which were for the surface water alone. Some of the river water is entrained by the counterdrift of sea water, and the time required for this water to make the complete circuit of the Bay is included in our average.

## Tidal Exchange Calculation

The empirical method for computing exchange ratios and the accumulation of fresh water in an estuary, as previously described by Ketchum (1951) has also been applied to the Bay of Fundy.

In this calculation it is necesssry to subdivide the estuary into segments which are horizontally defined by the width of the estuary and the average excursion of a particle of water on the flooding tide. In each segment so defined the exchange ratio, $r_n$, is given by:

$$r_n = \frac{P_n}{P_n + V_n} \tag{1}$$

in which $P_n$ is the intertidal volume, and $V_n$ is the low tide volume of the $n$th segment.

If the mixing is sufficiently vigorous so that all of the water within the segment is diluted with river water, the total quantity of fresh water, $Q_n$, accumulated within each segment is equal to:

$$Q_n = \frac{R}{r_n} \tag{2}$$

in which R is the quantity of fresh water introduced by the rivers during a complete tidal cycle. It has been shown that the water below 100 meters in the Bay of Fundy is only slightly diluted, and the segmentation has been made excluding the waters at greater depths.

### SEGMENTATION

The Bay of Fundy has been subdivided into tidal excursion segments from the head of tide in the Petitcodiac River and in Minas Basin to a diagonal line to the southwest of Grand Manan. The location of the segments so obtained is shown in Figure 7 and their lengths are included in Table II. The northern arm of the Bay is thus subdivided into seven segments, including two in the Cumberland Basin (2a and 2b), and Minas Basin is subdivided into six segments. The

Bay of Fundy between Cape Chignecto and the southern end of Grand Manan is divided into twelve segments.

These segments are computed from the displacement expected from the volume of water introduced as the tide floods, and the length of each should equal the mean excursion during the flooding tide. This method will give erroneous results if the tidal currents are restricted to part of the water column. Comparisons with direct current measurements are therefore desirable to check the size of the segments. It will be noted that Segment 2 in the Petitcodiac River has a length of 23 miles. The tidal bore in the Petitcodiac River runs for a distance of

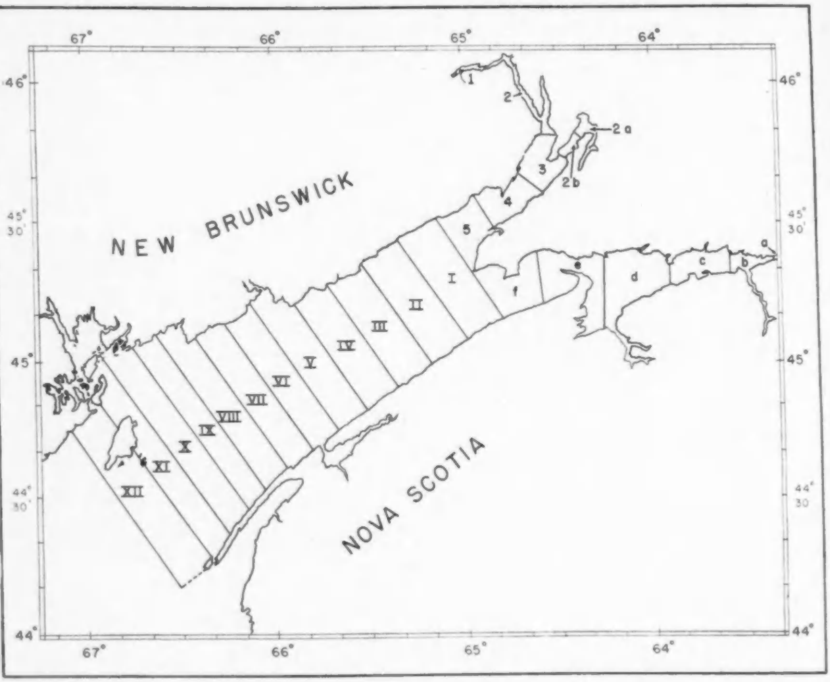


FIGURE 7. The location of the tidal-excursion segments in the Bay of Fundy area.

21 miles in the neighbourhood of this segment. (U.S. Navy Dept., 1939). At the mouth of the Petitcodiac River the maximum tidal velocities are 3 to 4 knots giving excursions[1] of 10 to 14 miles, and in Chignecto Bay the tidal currents have average velocities of about 2 knots, producing excursions of about 8 miles. In this region our tidal segments range from 9.3 to 11.5 miles in length. In Minas Basin the tidal currents have average velocities of 3 to 4 knots, giving mean excursions of 12 to 16 miles. Our segment lengths range from 13.7 at the upper end to 15.3 miles for the outermost segments.

[1]Calculated as $\frac{2}{\pi}$ × average maximum velocity × 6.2 hours. Maximum spring-tide velocities are multiplied by 0.85 to convert them to average maximum velocities.

Within the Bay of Fundy the length of the segments decreases from 10 miles at Cape Chignecto to 6.5 miles at Grand Manan. The final segment is again greater, being 9 miles in length. The average length is 7.7 miles. The current tables of the U.S. Coast and Geodetic Survey give average velocities at strength of currents within this area which range from 1.5 to 2 knots, giving excursions ranging from 5.9 to 7.9 miles. In Grand Manan Channel the velocity is 2.4 knots, or 9.5 miles for the excursion. To the south of Grand Manan the observed currents are 2.6 to 3.3 knots, giving excursions of 10.3 to 13 miles. These stations are outside of our outermost segment which was 9 miles in length, but they indicate that the excursions in this area may be expected to increase. It appears, therefore, that the tidal excursions computed from volume displacements by this method are comparable to excursions derived from measured currents.

TABLE II. Intertidal and high-tide volumes and exchange ratios of various tidal exchange segments of the Bay of Fundy. (For location of segments, see Figure 7.)

| | Segment | Distance [a] | Length of segment | Intertidal volume | High tide volume | Exchange ratio |
|---|---|---|---|---|---|---|
| | | *miles* | *miles* | $10^9 ft.^3$ | $10^9 ft.^3$ | $r_n$ |
| Chignecto Bay | 0 | 64.2 | — | 0.32 | 0.34 | 0.95 |
| | 1 | 54.8 | 9.4 | 3.81 | 4.0 | 0.95 |
| | 2 | 31.3 | 23.5 | 33.8 | 37.8 | 0.85 |
| | 2a | 34.8 | — | 6.7 | 7.4 | 0.91 |
| | 2b | 29.8 | 5.0 | 23.9 | 30.6 | 0.78 |
| | 3 | 20.8 | 10.5 | 122 | 190 | 0.64 |
| | 4 | 9.3 | 11.5 | 100 | 290 | 0.346 |
| | 5 | 0 | 9.3 | 100 | 390 | 0.256 |
| Minas Basin | a | 66.9 | — | 2.63 | 2.8 | 0.94 |
| | b | 57.5 | 9.4 | 29.4 | 32.2 | 0.92 |
| | c | 43.8 | 13.7 | 102.8 | 135 | 0.76 |
| | d | 29.8 | 14.0 | 205 | 340 | 0.604 |
| | e | 15.3 | 14.5 | 220 | 560 | 0.392 |
| | f | 0 | 15.3 | 170 | 730 | 0.233 |
| Bay of Fundy | I | 10.0 | 10.0 | 200 | 1380 | 0.151 |
| | II | 19.0 | 9.0 | 200 | 1520 | 0.132 |
| | III | 28.0 | 9.0 | 200 | 1720 | 0.116 |
| | VI | 36.5 | 8.5 | 200 | 1920 | 0.104 |
| | V | 44.0 | 7.5 | 200 | 2120 | 0.094 |
| | VI | 51.0 | 7.0 | 200 | 2320 | 0.086 |
| | VII | 57.5 | 6.5 | 200 | 2520 | 0.080 |
| | VIII | 64.0 | 6.5 | 200 | 2720 | 0.074 |
| | IX | 70.5 | 6.5 | 200 | 2920 | 0.069 |
| | X | 77.0 | 6.5 | 200 | 3120 | 0.064 |
| | XI | 83.5 | 6.5 | 200 | 3320 | 0.060 |
| | XII | 92.5 | 9.0 | 280 | 3600 | 0.056 |

[a]From Cape Chignecto to outer boundary of segment.

EXCHANGE RATIOS

The volumes within each of these segments and the appropriate exchange ratios are presented in Table II. In the Petitcodiac River and the upper end of Minas Basin, where the range of tides becomes 40 feet, the exchange ratios are 0.95 and 0.94 respectively. In the neighbourhood of Cape Chignecto the exchange ratio is 0.15, and it falls gradually as a result both of increasing depth and decreasing tidal range to a value of 0.056 in the segment immediately south of Grand Manan.

ACCUMULATION OF FRESH WATER

The fact that the St. John River contributes the major portion of the fresh water to the Bay near its center complicates the calculation of the accumulation of fresh water. Water at all depths in the neighbourhood of the St. John River is

TABLE III. Volume of river water accumulated within the various segments of the Bay of Fundy.

| | Segment | River flow | St. John[a] water | River water accumulated | Cumulative river water |
|---|---|---|---|---|---|
| | | $10^9 ft.^3/T.C.$ | $10^9 ft.^3$ | $10^9 ft.^3$ | $10^9 ft.^3$ |
| Chignecto Bay | 0 | 0.32 | 0.003 | 0.34 | 0.343 |
| | 1 | | 0.061 | 0.34 | 0.744 |
| | 2 | | 0.571 | 0.38 | 1.695 |
| | 2a | | 0.112 | 0.35 | |
| | 2b | | 0.461 | 0.41 | |
| | 3 | | 2.87 | 0.50 | 6.40 |
| | 4 | | 4.37 | 0.90 | 11.67 |
| | 5 | | 5.89 | 1.25 | 18.81 |
| Minas Basin | a | 0.45 | 0.042 | 0.48 | 0.522 |
| | b | | 0.484 | 0.49 | 1.50 |
| | c | | 2.04 | 0.59 | 4.13 |
| | d | | 5.14 | 0.75 | 10.02 |
| | e | | 8.45 | 1.15 | 19.62 |
| | f | | 11.0 | 1.92 | 32.55 |
| Bay of Fundy | I | 0.77 | 20.0 | 5.14 | 76.5 |
| | II | | 23.0 | 5.8 | 105.3 |
| | III | | 26.0 | 6.6 | 137.9 |
| | IV | | 29.0 | 7.4 | 174.3 |
| | V | 4.08 | | 43.4 | 217.7 |
| | VI | | | 47.4 | 265.1 |
| | VII | | | 51.4 | 316.5 |
| | VIII | | | 55.5 | 372.0 |
| | IX | | | 59.6 | 431.6 |
| | X | | | 63.9 | 495.5 |
| | XI | | | 67.9 | 563.4 |
| | XII | | | 73.4 | 636.8 |

[a]River water introduced into upper part of estuary in counter-flow of sea water; 1.51% of high-tide volume.

diluted with river effluent. It is this diluted sea water which provides the source of the countercurrent and is involved in the mixing in the upper part of the Bay. Inspection of the figures showing the distributions of salinity and fresh water indicates that the source sea water for the part of the Bay to the northeast of the St. John River has a salinity of approximately 32.5 rather than the salinity of 33 ‰ which appears appropriate for the lower part of the Bay. This decreased salinity corresponds to the incorporation of 1.51 per cent river water, most of which must originate in the St. John. The Bay of Fundy has therefore been treated as though it were two estuaries in tandem. All of the water in the upper part of the estuary is assumed to contain 1.51 per cent river water derived from the St. John River. To this volume of river water we have added the quantity of river water which would be expected to accumulate as a result of the river flow from the drainage basins discharging into Chignecto Bay and Minas Basin.

The results of the computation of the total accumulation of fresh water in the Bay of Fundy are presented in Table III. These calculations have been made using, as above, the river flow for the period April to July, as given by Watson (1936). The computed accumulation of fresh water is $636.8 \times 10^9$ cubic feet, which corresponds to nearly 81 times the daily contribution of all of the drainage basins. Between Cape Chignecto and the line south of Grand Manan the calculated accumulation is $585 \times 10^9 ft.^3$. The computed flushing time of this part of the area is thus about 74 days. These values correspond to those computed from the salinity distribution; namely, $600 \times 10^9 ft.^3$ for the accumulation and 76 days for the flushing time.

## Comparison of Calculations with Observations

### FRESH WATER

A direct comparison between the calculated and observed accumulation of water in the Bay of Fundy is shown in Figure 8. The quantity of fresh water computed to be present in Chignecto Bay and Minas Basin is included, although the salinity data necessary to check these computations are not available. The quantities of river water deduced from the salinity distribution were read for the appropriate distances from Figure 6.

The numbers recorded above the correlation line indicate the average flushing time in days for the observed quantity of fresh water. The numbers below the correlation line show the distance in nautical miles from Cape Chignecto. The correlation between calculated and observed accumulation of river water is very close throughout the entire length of the Bay of Fundy.

It will be remembered that the tidal-exchange calculation was made excluding the water below a depth of 100 meters. If this deeper water were included in the computation the results for the first seven segments would not be affected, but six shorter segments would be substituted for the final five segments. The total computed accumulation of river water would be increased by $76 \times 10^9 ft.^3$. The data in Table I show that only $10 \times 10^9 ft.^3$ are to be found at depths greater than 100 meters. On both the basis of the observed distribution of salinity and the tidal excursions discussed previously, therefore, the exclusion of this deeper water from the calculations seems justifiable.

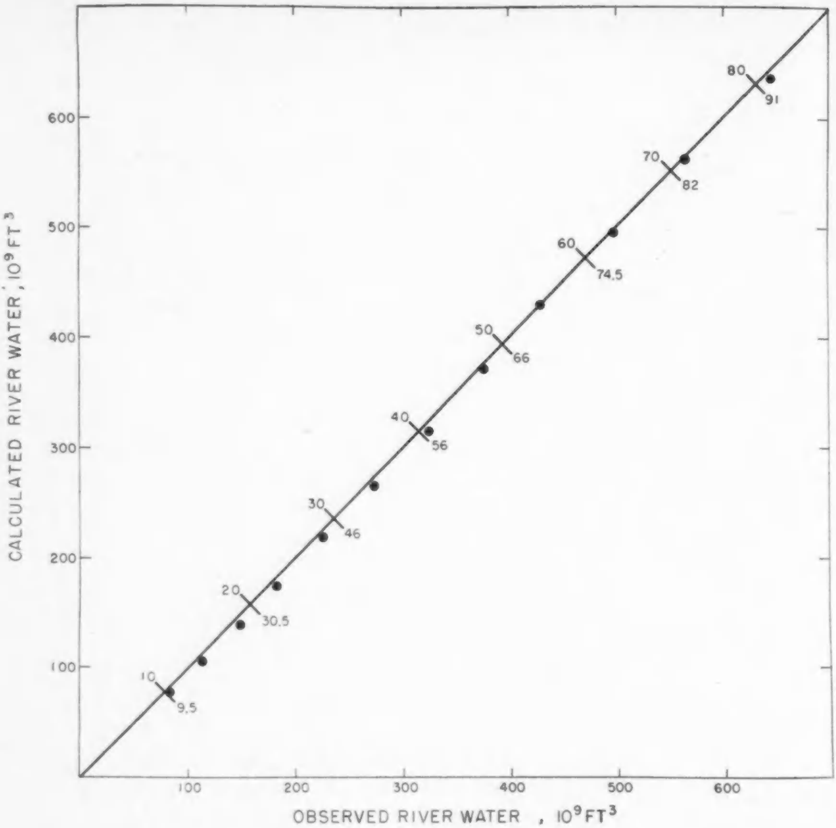


FIGURE 8. Comparison between the observed and the calculated accumulation of river water in the Bay of Fundy. The numbers above the correlation line show the average flushing time in days; those below the line show the distance, in nautical miles, from Cape Chignecto.

EXCHANGE RATIOS

An exchange ratio ($r$) can also be computed from observed distribution of fresh water as follows:

$$r = \frac{R}{Q} \tag{3}$$

where Q is the observed quantity of fresh water as derived from the salinity distribution and R is the volume of water introduced by the river during a tidal cycle. This calculation must also be made separately for each of the tidal-excursion segments, since any variation in the size of the segments considered will have a direct effect on the value of Q. It will be recognized that this equation is identical with equation (2), but we are using different basic data for the calcul-

ation. In this case the observed distribution of river water is used to calculate an exchange ratio; in applying equation (2), an exchange ratio calculated from tidal volumes was used to compute a theoretical distribution of river water.

In Figure 9 the exchange ratios calculated from the tidal volumes and from the observed distribution of fresh water are plotted for various distances from Cape Chignecto. Close agreement between the exchange ratios calculated by the two methods is obtained. The values decrease in a regular way from about 0.15 at Cape Chignecto to about 0.056 south of Grand Manan.

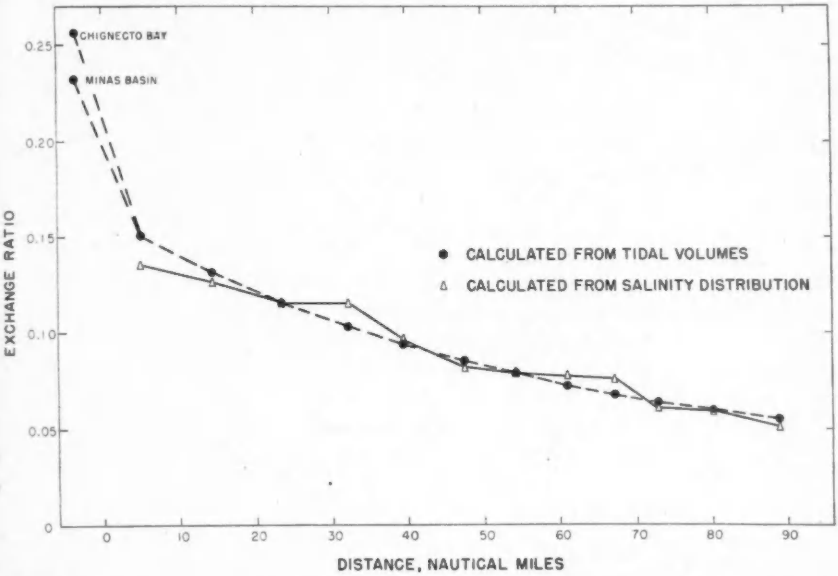


FIGURE 9. The exchange ratios calculated from the observed distribution of river water and from the tidal volumes for various distances from Cape Chignecto.

## DISCUSSION

It should be emphasized that the exchanges and the derived flushing times given above are averages for complete cross-sections of the estuary. The circulation in the Bay of Fundy clearly indicates that there is a net inflow of more saline water along the Nova Scotia shore, with the river water mainly escaping along the New Brunswick shore. It is clear that, depending upon which side of the estuary is being considered, the actual exchanges will vary from the average by large amounts. They will be greater along the New Brunswick shore and less along the Nova Scotia shore. There appears to be no very certain method of determining how great this variation from the average may be.

It should also be pointed out that although the foregoing conclusions were based upon the distribution of river water, the same exchanges may be expected for any material or organism freely transported by the water. The effect of the

circulation on the biological populations present could be evaluated by methods similar to those discussed by Ketchum (1952), using the average exchange ratios presented in this paper.

One of the purposes of this investigation was to determine whether the simplified empirical method of calculating exchanges in a tidal estuary and the resultant accumulation of river water would apply to the Bay of Fundy. The agreement between the calculated and observed accumulations of river water is very close when the calculation is made excluding the water deeper than 100 meters. One of the basic assumptions in the empirical calculation is that the water is thoroughly mixed in a segment defined by the sides of the estuary and the average excursion of a particle of water on the flood tide. It seems logical that this sets the maximum distance over which complete mixing can be expected. If, however, mixing is complete over a shorter distance, the computed accumulation of river water would be less than the actual accumulation. The fact that the computed and observed distributions agree in the Bay of Fundy indicates that mixing is sufficiently vigorous so that the assumption of the tidal-excursion segment as a mixing length gives valid results.

The Bay of Fundy is much larger than the estuaries previously discussed. The success of the tidal-exchange calculation in this region indicates that it is not limited to the smaller estuaries and suggests that it may be useful in any estuary having vigorous tidal mixing. Some characteristics of the estuaries previously discussed by Ketchum (1951) are compared with the Bay of Fundy in Table IV.

TABLE IV. Some characteristics of the estuaries in which the tidal-exchange calculation has been satisfactory.

| Characteristic | Previous range[a] | Bay of Fundy |
|---|---|---|
| Surveyed length—*nautical miles* | 1.5 to 20 | 90 |
| Surface area—*sq. nautical miles* | 1 to 45 | 3,300 |
| Max. high tide depth—*feet* | 9 to 1000 | 630 |
| Depth of diluted water —*feet* | 5 to 40 | > 300 |
| Range of tides—*feet* | 1.5 to 6.4 | 14 to 40 |
| Tidal prism volume—$10^6 ft.^3$ | 7.6 to 9200 | 3,670,000 |
| River flow per tidal cycle—$10^6 ft^3$ | 0.5 to 120 | 4,080 |
| Ratio $\frac{\text{Prism volume}}{\text{River flow}}$ | 15 to 279 | 900 |

[a]The extreme values for Raritan River and Bay, Alberni Inlet, and Great Pond, previously discussed by Ketchum, 1951.

The volume of the tidal prism in the Bay of Fundy is about 400 times greater than that in Raritan Bay, the largest previous value. The volume of river water introduced during a tidal cycle is nearly 40 times greater than that introduced into Alberni Inlet, the largest previous value. The ratio of tidal-prism volume to river flow is 60 times as great as the smallest, and more than three times as great as the largest value discussed in the previous paper.

In the estuaries previously studied the depth of the water which was measure-

ably diluted with river water was 40 feet or less. In the Bay of Fundy dilution of the sea water with river water is detectable at depths greater than 100 meters. This observation emphasizes the vigorous vertical mixing which occurs in the Bay of Fundy.

## PASSAMAQUODDY BAY

The details of the circulation of waters in Passamaquoddy Bay have been less thoroughly studied than in the Bay of Fundy. Passamaquoddy Bay, shown in Figure 10, is a nearly enclosed body of water which receives the drainage from three major basins, the St. Croix, the Digdequash, and the Magaguadavic. Although a number of hydrographic observations have been made within the Bay, no systematic attempt at a quantitative description of the circulation has been made. Watson comments that most of the fresh water escapes from Passamaquoddy Bay through the Western Passage, but he makes no attempt to evaluate the quantity of this discharge. Copeland (1909), and Craigie (1914), conducted salinity and temperature surveys of the St. Croix River. Hachey (1934a, 1935) has described the mixing of fresh and salt water in estuaries, with special reference to parts of Passamaquoddy Bay.

### The St. Croix Estuary

The St. Croix is the largest of the three rivers, producing one and one-half times as much fresh water as the other two combined. Entering as it does on the western side of Passamaquoddy Bay, the effluent from the St. Croix would tend to establish and maintain a counterclockwise circulation in much the same way the St. John does for the Bay of Fundy. The waters in the estuary of the St. Croix, and in the Bay off its mouth, are fresher than those found in any other part of Passamaquoddy Bay.

The exchanges of water in the St. Croix estuary have been evaluated by methods similar to those used for the Bay of Fundy. The results of the tidal-exchange calculation are given in Table V. The river is divided into five segments

TABLE V. The St. Croix Estuary. Intertidal and high-tide volumes, exchange ratios and accumulation of river water when the river flow is $104 \times 10^6 ft.^3$ per tidal cycle. For location of segments see Figure 10; segments A, B, C, are in Oak Bay.

| Segment No. | Distance from mouth | Intertidal volume | High-tide volume | Exchange ratio | River water Local | River water Cumulative |
|---|---|---|---|---|---|---|
| | *miles* | $10^9 ft.^3$ | $10^9 ft.^3$ | $r_n$ | $10^9 ft.^3$ | $10^9 ft.^3$ |
| 0 | 13.1 | 0.104 | 0.115 | 0.905 | 0.115 | 0.115 |
| I | 10.2 | 0.786 | 0.905 | 0.870 | 0.120 | 0.235 |
| A | 12.0 | 0.20 | 0.25 | 0.80 | 0.130 | — |
| B | 10.3 | 1.13 | 1.33 | 0.860 | 0.121 | — |
| C | 8.4 | 1.37 | 2.70 | 0.506 | 0.206 | 0.692 |
| II | 6.2 | 2.21 | 5.82 | 0.38 | 0.273 | 0.965 |
| III | 2.8 | 2.60 | 8.40 | 0.31 | 0.336 | 1.301 |
| IV | 0 | 3.60 | 12.0 | 0.30 | 0.348 | 1.649 |

from the head of tide at Calais to the mouth at St. Andrews. Three additional tidal segments are found in Oak Bay. The location of these segments is shown in Figure 10. The exchange ratio decreases from 0.905 at Calais to 0.30 at St. Andrews.

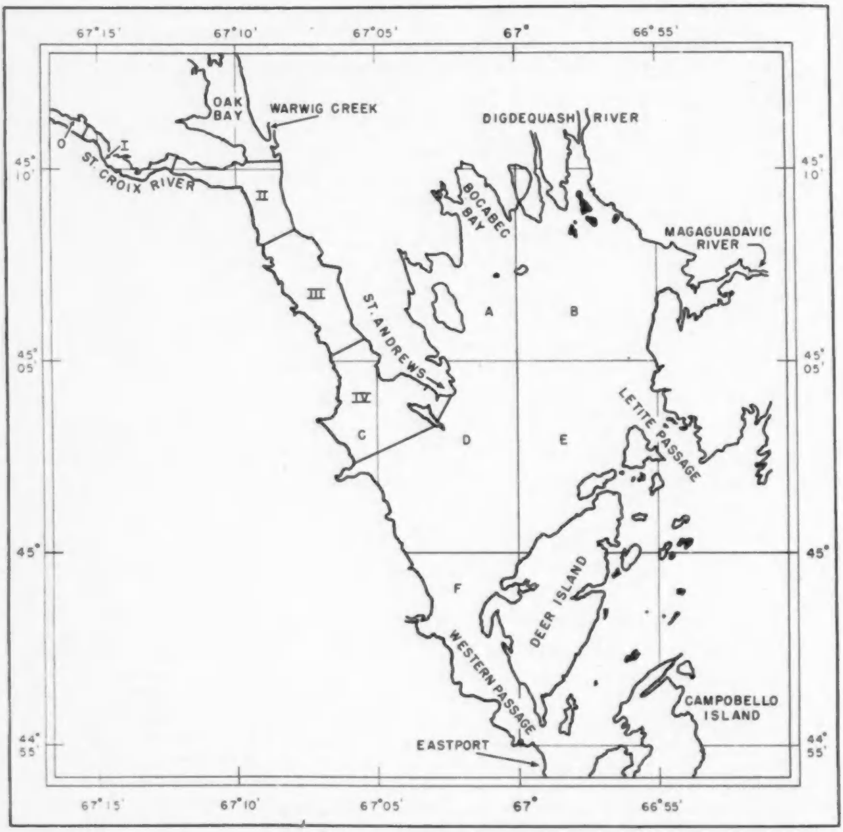


FIGURE 10. Passamaquoddy Bay. The letters in the five-minute squares correspond to those in Table IV. The numbered segments in the St. Croix River correspond to those in Table V and VI.

The St. Croix River is gauged near Baileyville, Maine, and the office of the Geological Survey at Augusta, Maine, has made available the river-flow data prior to its publication. For the first 17 days of August, 1951, the gauged flow averaged 2,320 ft.$^3$/sec., or 104 x $10^6$ft.$^3$/tidal cycle. Using this value for the river flow, the quantity of river water accumulated in the estuary between Calais and St. Andrews is calculated to be about 1,650 x $10^6$ cubic feet.

During August, 1951, a series of salinity and temperature observations were

made in the estuary of the St. Croix, and the results are given in the appendix. The data from the stations marked with an asterisk were used in computing the average high-tide salinities and volumes of fresh water in the various tidal-excursion segments. The mean salinity and fresh-water content of the tidal-excursion segments are given in Table VI. The salinity results indicate that about

TABLE VI. Mean salinities and volumes of river water accumulated in the various tidal-exchange segments of the St. Croix Estuary, August, 1951.

| Segment No. | Stations used | Mean salinity | River water | River water Local | River water Cumulative |
|---|---|---|---|---|---|
| | | ‰ | % | $10^9 ft.^3$ | $10^9 ft.^3$ |
| 0 | R-1 | 12.785 | 60.0 | 0.069 | 0.069 |
| I | R-2 | 26.18 | 18.2 | 0.165 | 0.234 |
| A | | | | | |
| B | R-3a | 28.86 | 9.82 | 0.420 | 0.654 |
| C | | | | | |
| II | R-3, R-4 | 29.83 | 6.78 | 0.394 | 1.048 |
| III | R-4, R-4a | 30.72 | 4.00 | 0.282 | 1.330 |
| IV | R-5, R-6 | 31.14 | 2.69 | 0.323 | 1.653 |

1,650 x $10^6$ cubic feet of river water was present in the stretch between Calais and St. Andrews. A direct comparison between the computed and observed quantities of river water in the St. Croix estuary is given in Figure 11. The agree-

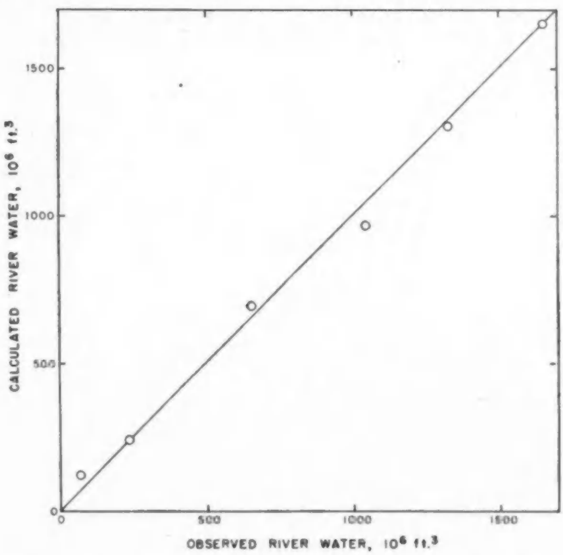


FIGURE 11. Comparison between the observed and the calculated volumes of fresh water in the St. Croix Estuary.

ment between the observed and calculated values indicates that the exchange ratios computed from tidal volumes are adequate to explain the observed distribution.

The flushing times of the various segments range from a little more than one tidal cycle for the segment near Calais, to about three tidal cycles near St. Andrews. For the entire length of the estuary considered, about 15 tides, or 8 days are required, on the average, to replace one day's river flow.

## Passamaquoddy Bay

Passamaquoddy Bay proper has been subdivided into volumes bounded by lines drawn at five-minute intervals. The available salinity data have been summarized for the following depth ranges: surface to 25 meters, 25 to 50 meters, and greater than 50 meters. The volume, mean salinity, and percentage of river water for each one of these parts of Passamaquoddy Bay are listed in Table VII.

Table VII. Average salinities and quantities of river water in various segments of Passamaquoddy Bay. (The location of the segments is shown in Figure 10.)

| Segment | Depth | Total volume | Mean salinity | River water[a] | River water | Mean flushing time |
|---|---|---|---|---|---|---|
| | *meters* | $10^9 ft.^3$ | ‰ | % | $10^9 ft.^3$ | *days* |
| A | 0–25 | 12.49 | (31.47) | (2.72) | 0.34 | |
| | 25–50 | 1.36 | (31.65) | (2.16) | 0.029 | 1.98[b] |
| B | 0–25 | 25.50 | 31.47 | 2.72 | 0.695 | |
| | 25–50 | 3.58 | 31.65 | 2.16 | 0.077 | 4.15[b] |
| | > 50 | 0.01 | — | — | — | |
| D | 0–25 | 35.67 | 31.235 | 3.45 | 1.230 | |
| | 25–50 | 6.49 | 31.615 | 2.27 | 0.147 | |
| | > 50 | 0.02 | — | — | — | 3.45[c] |
| E | 0–25 | 33.65 | 31.61 | 2.29 | 0.77 | |
| | 25–50 | 13.79 | 32.21 | 0.43 | 0.059 | 4.45[b] |
| | > 50 | 1.70 | — | — | — | |
| F | 0–25 | 16.48 | 31.49 | 2.66 | 0.44 | |
| | 25–50 | 10.69 | 31.72 | 1.95 | 0.208 | |
| | > 50 | 5.20 | 32.10 | 0.77 | 0.039 | 1.78[c] |

[a]Reference salinity 32.35 o/oo.
[b]Using river flow of Digdequash and Magaguadavic Rivers ($0.186 \times 10^9 ft.^3$/day).
[c]Using river flow of Digdequash, Magaguadavic and St. Croix Rivers ($0.387 \times 10^9 ft.^3$/day).

For the calculations of the percentage of fresh water a base salinity of 32.35 ‰ has been used. This was the average salinity of the water deeper than 25 meters in the channel between Deer Island and Campobello Island. It was assumed that this deep water was the source sea water for mixing inside of Passamaquoddy Bay.

The deep water in the area marked E in Figure 10 was always more saline than any other water within the Bay. This is in agreement with Huntsman's conclusion (personal communication) that the high-salinity water enters Passamaquoddy Bay through Letite Passage.

The total volume of river water within the Bay, exclusive of the St. Croix estuary, was about $4 \times 10^9 ft.^3$. On the basis of the drainage of the Digdequash and Magaguadavic Rivers alone this corresponds to a mean flushing time of 21.6 days. If, on the other hand, it is assumed that the river flow from the St. Croix becomes uniformly mixed throughout this area, a mean flushing time of about 10 days is obtained.

Inspection of Figure 10 suggests that the St. Croix outflow should be included in the calculations for the areas marked D and F, but should not be included for the others. The calculation has been made in this way in Table VII, and gives a mean flushing time for Passamaquoddy Bay of 15.8 days.

Although it is impossible to determine precisely how the river flow should be utilized in interpreting the circulation in a complex area such as this, it seems probable that a flushing time of about 15 days should be approximately correct.

### Exchanges with the Bay of Fundy

It may also be desirable to evaluate the relative discharge from Passamaquoddy Bay through the two main passages. Available current observations are inadequate to provide the necessary information. An approximation can be made, however, from the salinity data provided by Watson (1936). In July, 1932, he made simultaneous observations at high and low, half flood, and half ebb tides, from two boats in the two passages. We have drawn cross-sections of the passages at the location of his station and determined the total cross-sectional area. From the averages of his salinity data it is possible to calculate the mean proportion of fresh water and consequently the part of the cross-sectional area which would be occupied by the fresh water if it were possible to separate it from the salt. The results are presented in Table VIII and show that of the total cross-sectional area of 782,000 square feet in the Western Passage, 0.82 per cent or 6,430 $ft.^2$ would be occupied by the fresh water. Similarly, of 209,000 square feet of Letite Passage, 0.99 per cent or 2,070 $ft.^2$ were occupied by fresh water. If it is assumed that the transport through the passages is proportional to the quantity of fresh water present, then 75.6 per cent of the river water contributed to Passamaquoddy Bay escapes through the Western Passage, and 24.4 per cent escapes through Letite Passage. It should be recognized that this assumption implies that the non-tidal drift through the two passages is equal. There are no data to substantiate this assumption.

From the proportion of fresh water in each cross-section the total volume of water which must escape in order to discharge one river flow during a complete tidal cycle is given by:

$$E = 100R/F$$

in which E is the total volume of water escaping each tidal cycle, R is the volume

TABLE VIII. Transport of water through the passages into Passamaquoddy Bay in July, 1932, when the total river flow was 2,932 ft.$^3$/sec., or 131 $\times$ $10^6$ft.$^3$ per tidal cycle.

| | LOCATION OF SECTIONS | | | |
|---|---|---|---|---|
| | Western Passage | | Letite Pass. | E. Quoddy Head |
| | Inner end | Outer end | Inner end | to Muscabin Point |
| Area of section (A) $10^4$ft.$^2$ | 7.82 | 49.3 | 20.9 | 506 |
| Fresh water (F) % | 0.82 | 0.23 | 0.99 | 0.17 |
| Area fresh $\left(\frac{AxF}{100}\right)$ $10^4$ft.$^2$ | 0.643 | 0.112 | 0.207 | 0.96 |
| River flow (R) $10^6$ft.$^3$/tidal cycle | 99 | 99 | 32 | 131 |
| Escaping volume $\left(E = \frac{100R}{F}\right)$ $10^6$ft.$^3$/T.C. | 12,100 | 43,000 | 3,200 | 77,000 |
| Non-tidal drift $\left(\frac{E}{A}\right)$ $10^3$ft./T.C. | 15.5 | 55.2 | 15.5 | 15.2 |

of river water exchanged per tidal cycle, and F is the mean per cent of fresh water in the mixture (Hachey, 1935; Ketchum, 1951). These calculations have been made for the inner ends of the passages, for a station near the outer end of the Western Passage, and for a cross-section running from East Quoddy Head to Muscabin Point. For the inner end of Western Passage the escaping volume of mixed water is 122 times as great as the river flow. This increases almost fourfold within the Passage so that at the southern end the escaping volume is 435 times the river flow. In Letite Passage the escaping volume is 100 times the river flow. The combined volume of fresh water discharged through both passages must also escape through the section running between East Quoddy Head and Muscabin Point. Here the entrained sea water is 588 times the river-flow volume. Using the average river flow for July, 1932, as given by Watson, the corresponding volumes of mixed water range from 12 x $10^9$ to 77 x $10^9$ft.$^3$ per tidal cycle (270,000 to 1,720,000 ft.$^3$/sec.). These results are included in the data given in Table VIII.

The non-tidal drift of the water results from inequalities of either the duration or velocity of flood and ebb currents. The non-tidal drift must be sufficient to remove the fresh water added by the rivers during a tidal cycle. It has been mentioned that the assumption concerning the proportion of water moving through each passage imposes the condition that the non-tidal drifts be equal. The computed rate of this drift is 15,500 ft., or about 2.5 miles per tidal cycle of 12.4 hours. It is interesting that the non-tidal drift for the section between East Quoddy Head and Muscabin Point, through which all of the water must pass, is nearly equal to that calculated for the inner ends of the two passages. At the outer end of the Western Passage the computed rate of non-tidal drift is much greater. This is necessary to remove the large volume of sea water which becomes

entrained in the flow within the Passage. The velocities of the tidal currents show a similar increase. The maximum velocity for mean tides near the inner end of the Passage is 1.9 knots, while the comparable value for the velocity at the outer end is 3.1 knots (United States Coast and Geodetic Survey).

## Discussion

The same general comments which were made in the discussion of the Bay of Fundy data (page 113) apply to the St. Croix estuary and Passamaquoddy Bay. The observation that about eight days are required on the average to exchange the water within the St. Croix estuary between Calais and St. Andrews, and that an additional 16 days are required for the exchange of water in Passamaquoddy Bay may aid in the interpretation of the interesting distributions of biological populations in these areas.

The major uncertainty in this area appears to be the actual quantities of water exchanged through the various passages between Passamaquoddy Bay and the Bay of Fundy. The conclusions we have drawn concerning this process are based upon assumptions which it is impossible to check with the available data. It seems clear, however, that the mixing in the Western Passage of Passamaquoddy Bay is very vigorous, since in traversing a little over two miles of this Passage this water becomes mixed with about four times its own volume of sea water. This is in agreement with observable hydrographic conditions, since this is a region of rapid tidal flow, and boils and whirlpools are frequently observed which indicate locations where active admixture of deep water is taking place. It would be very desirable to have complete series of current measurements and samples to determine the salinity of the water in each of the two main passages. From such data the actual transports, and the proportion of river water escaping through the two passes could be determined.

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# APPENDIX

Salinities and Temperatures in the St. Croix Estuary, August, 1951.

| Date | Station | Location | Time after HW, ref. St. Andrews | | Depth | Salinity | Temp. |
|---|---|---|---|---|---|---|---|
| | | | *hours* | *min.* | *meters* | ‰ | °C. |
| Aug. 15 | R–1 | 45°11.1′N | | 33[a] | 0 | 1.19 | 20.56 |
| | | 67°15.6′W | | | 5 | 24.38 | 15.00 |
| Aug. 15 | R–2 | 45°09.7′N | | 48[a] | 0 | 14.11 | |
| | | 67°13.6′W | | | 4 | 27.36 | |
| | | | | | 9 | 28.35 | |
| | | | | | 14 | 29.38 | |
| Aug. 15 | R–3 | 45°09.7′N | 1 | 33[a] | 0 | 24.07 | 16.67 |
| | | 67°09.5′W | | | 4 | 28.49 | 14.56 |
| | | | | | 9 | 30.55 | 13.33 |
| | | | | | 14 | 30.91 | 13.29 |
| Aug. 15 | R–3 | 45°09.7′N | 4 | 53 | 0 | 23.26 | 16.67 |
| | | 67°09.5′W | | | 5 | 27.65 | 14.80 |
| | | | | | 15 | 29.94 | 13.89 |
| Aug. 15 | R–3a | 45°11.6′N | 3 | 08[a] | 0 | 26.94 | 16.50 |
| | | 67°10.0′W | | | 5 | 28.46 | 14.39 |
| | | | | | 10 | 29.92 | 14.10 |
| | | | | | 14 | 29.90 | 14.00 |
| Aug. 15 | R–3b | 45°10.9′N | 2 | 28 | 0 | 28.26 | 15.28 |
| | | 67°08.7′W | | | 5 | 28.37 | 14.85 |
| Aug. 15 | R–4 | 45°07.9′N | 5 | 38 | 0 | 25.41 | 16.67 |
| | | 67°07.6′W | | | 5 | 28.59 | 13.85 |
| | | | | | 10 | 30.61 | 13.61 |
| | | | | | 15 | 30.75 | 13.57 |
| | | | | | 25 | 30.90 | 13.47 |
| Aug. 21 | R–4 | 45°07.9′N | | 19[a] | 0 | 29.88 | 15.00 |
| | | 67°07.6′W | | | 5 | 29.83 | 14.05 |
| | | | | | 10 | 30.41 | 13.67 |
| | | | | | 20 | 30.97 | 13.42 |
| | | | | | 30 | 31.20 | 13.28 |
| Aug. 21 | R–4a | 45°06.4′N | | 46[a] | 0 | 30.30 | 14.44 |
| | | 67°06.6′W | | | 5 | 30.57 | 13.86 |
| | | | | | 10 | 30.79 | 13.47 |
| | | | | | 20 | 31.06 | 12.94 |
| | | | | | 25 | 31.44 | 12.89 |
| Aug. 15 | R–5 | 45°04.9′N | 6 | 08 | 0 | 28.01 | 15.56 |
| | | 67°06.0′W | | | 5 | 29.51 | 13.75 |
| | | | | | 10 | 30.70 | 13.33 |
| | | | | | 15 | 31.15 | 13.16 |
| | | | | | 25 | 31.53 | 13.11 |
| Aug. 21 | R–5 | 45°04.9′N | 1 | 11[a] | 0 | 30.93 | 13.89 |
| | | 67°06.0′W | | | 5 | 31.08 | 13.44 |
| | | | | | 10 | 31.13 | 13.29 |
| | | | | | 20 | 31.33 | 12.96 |
| | | | | | 25 | 31.46 | 12.83 |

[a]Data used to calculate accumulation of river water in the St. Croix Estuary.

Salinities and Temperatures in the St. Croix Estuary, August, 1951 (continued).

| Date | Station | Location | Time after HW, ref. St. Andrews | | Depth | Salinity | Temp. |
|---|---|---|---|---|---|---|---|
| | | | *hours* | *min.* | *meters* | ‰ | °C. |
| Aug. 21 | R-6 | 45°03.5′N | 1 | 41[a] | 0 | 30.62 | 14.17 |
| | | 67°05.4′W | | | 5 | 30.73 | 13.97 |
| | | | | | 10 | 30.90 | 13.42 |
| | | | | | 15 | 31.04 | 13.22 |
| | | | | | 25 | 31.51 | 12.91 |
| Aug. 21 | R-7 | 45°01.2′N | 2 | 16 | 0 | 30.39 | 14.44 |
| | | 67°03.2′W | | | 5 | 30.41 | 13.36 |
| | | | | | 10 | 31.22 | 12.92 |
| | | | | | 20 | 31.60 | 12.86 |
| | | | | | 30 | 31.58 | 12.83 |
| Aug. 17 | DR-1 | 45°10.5′N | | 03 | 0 | 15.44 | 15.56 |
| | | 66°57.7′W | | | 5 | 28.69 | 13.97 |
| Aug. 17 | DR-2 | 45°09.5′N | | 18 | 0 | 28.82 | 14.56 |
| | | 66°57.9′W | | | 2.5 | 28.82 | 14.18 |
| | | | | | 7.5 | 31.15 | 13.28 |
| Aug. 17 | DR-3 | 45°08.8′N | | 43 | 0 | 29.09 | 14.17 |
| | | 66°57.9′W | | | 5 | 29.54 | 13.41 |
| | | | | | 10 | 31.24 | 13.21 |
| | | | | | 15 | 31.36 | 13.07 |
| Aug. 17 | DR-4 | 45°08.1′N | 1 | 04 | 0 | 29.83 | 14.33 |
| | | 66°57.3′W | | | 5 | 29.85 | 13.47 |
| | | | | | 10 | 31.26 | 13.17 |
| | | | | | 15 | 31.46 | 13.06 |

[a]Data used to calculate accumulation of river water in the St. Croix Estuary.

# Seasonal Variation of Temperature and Salinity of Surface Waters of the British Columbia Coast[1]


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ABSTRACT

Grand monthly means of daily observations of surface sea-water temperature and salinity from twelve light stations along the British Columbia coast during the 13 years 1935 to 1948 have been analysed. In general the temperatures reach a minimum of 45°F. ± 1° (7.2°C. ± 0.5°) in January and February. The maximum varies from 50° to 64°F. (10° to 18°C.) in August. The warmest waters occur in bays protected from wind action, and the coldest waters occur in regions of turbulent mixing due to wind or strong currents. The salinity along the mainland coast is a minimum in early summer, associated with the maximum run-off from melting snow. Along the west coast of Vancouver Island the minimum occurs in mid-winter, associated with maximum precipitation which is not stored as snow in this region. At the southern and northern tip of the Queen Charlotte Islands there is little or no variation of salinity because there is no land drainage of consequence in the vicinity.

In passes between Georgia Strait and the sea where the waters are mixed to homogeneity by strong tidal currents the annual variation of temperature and salinity is reduced, and in some cases entirely suppressed.

On the west coast of Vancouver Island it is shown that the annual cycle is affected by the dominant winds and upwelling of deep ocean waters.


## INTRODUCTION

For a number of years daily observations of the temperature and salinity of the surface sea water have been made under the direction of the Pacific Oceanographic Group at stations on the British Columbia coast. The information is published annually as "Observations of Sea Water Temperature, Salinity and Density on the Pacific Coast of Canada" (1947–1952), and the amount of data now available is sufficient to warrant investigation to determine their significance. This paper embodies the results of a preliminary analysis which indicates the general trend of temperature and salinity values along the coast and may serve as a background for more detailed use or study of the data.

In addition an attempt has been made to account for the main features of the temperature and salinity cycles in terms of known geophysical principles. In some cases, however, the evidence from these surface-temperature and salinity data alone is insufficient to complete the explanations and the present discussion therefore points out several lines for further research into the principles governing the cycles in this region.

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Records are available from some localities since 1914 but in the majority of cases the systematic recording commenced about 1935. This study considers only data from 1935 to 1948 so that the data for the different stations have substantially equal statistical weight.

The locations of the observing stations are indicated in Figure 1, all but two of them being at lighthouses where the temperature observations are made and water samples obtained by the lightkeepers (Hollister, 1949, 1951 and 1952). The samples are taken from a depth of three feet on the rising tide, within one hour of the high water, during the daylight hours.

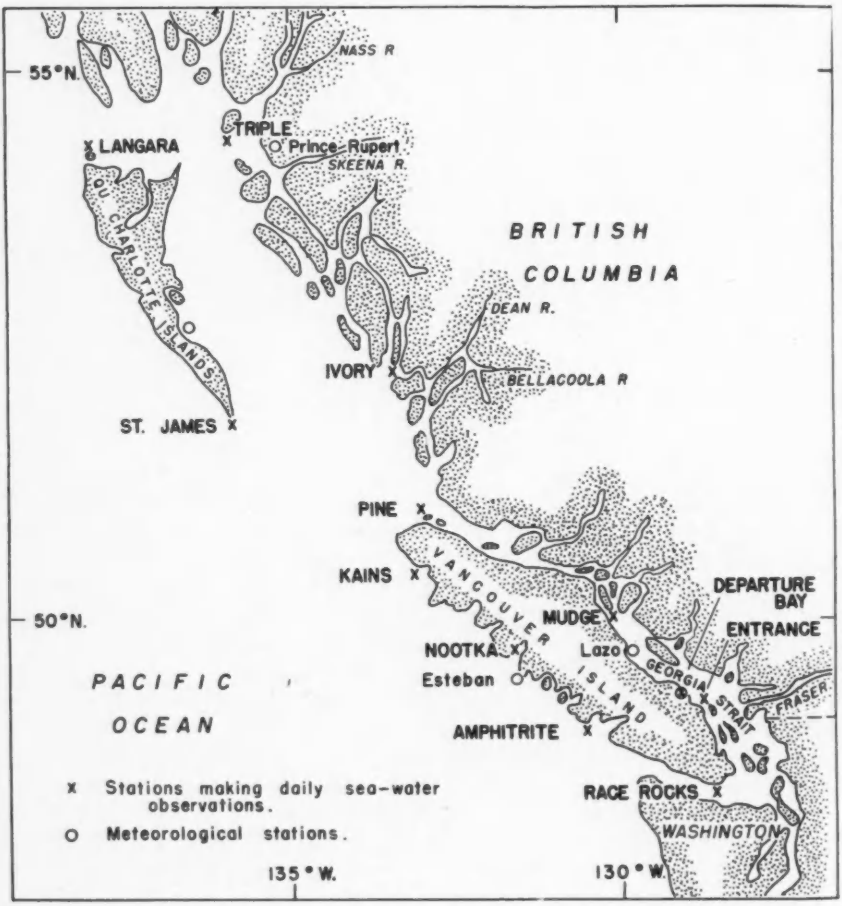


FIGURE 1. Chart showing location of stations making daily sea-water observations.

### Variation in Range of Surface Temperature

The seasonal variation in temperature reflects the variation in insolation during the year, but may be subject to a number of modifying influences including:

(1) variation in insolation with latitude,
(2) the effect of horizontal and vertical movements of water such as permanent currents, upwelling and turbulence,
(3) the degree of exposure of the station to wind and waves,
(4) evaporation and other factors not taken into account in detail in the present analysis.

For convenience in discussion the twelve stations are divided into three groups as:

| *Northern Group* | *West Coast Group* | *Georgia Strait Group* |
|---|---|---|
| Langara (Island) | Kains (Island) | (Cape) Mudge |
| Triple (Island) | Nootka (Island) | Departure Bay |
| (Cape) St. James | Amphitrite (Point) | Entrance (Island) |
| Ivory (Island) | | Race Rocks |
| Pine (Island) | | |

It will be shown that this grouping, which was in the first instance geographical, is also justified to some extent by the similarity in temperature and salinity cycles in each group, but that it is not the only grouping which can be devised.

### Annual Variation in Surface Temperatures

The general trend of the temperatures was obtained by calculating the mean temperature for each month's observation (monthly mean) and then the mean for all Januarys, all Februarys, etc. (grand monthly mean). Smoothed curves through the grand monthly means are plotted in Figures 2, 3 and 4 and indicate the general character of the annual temperature variations. The salient features are: (1) that maxima, and minima, occur within the same month at all stations except Mudge, where the maximum occurs in July, while the others all occur in August, (2) that while the minimum temperatures (in February) lie within the small range from 43.5°F. to 45.5°F. (6.4°C. to 7.5°C.), the maxima (in July/August) are more widely distributed from 50°F. to 64°F. (10.0°C. to 17.8°C.) and (3) consequently the annual range of temperature varies widely from station to station, from 5F.° (3C.°) at Pine Island to 20F.° (11C.°) at Departure Bay. If the data are taken year by year the more detailed examination presented in the following paragraphs shows that with minor exceptions the character of the temperature cycle exhibited by the grand monthly means is also typical of that for individual years.

### Year-to-Year Fluctuations

In Figure 5 are given values of the standard deviations of the monthly means. This quantity is a measure of the year-to-year deviation of the monthly mean from

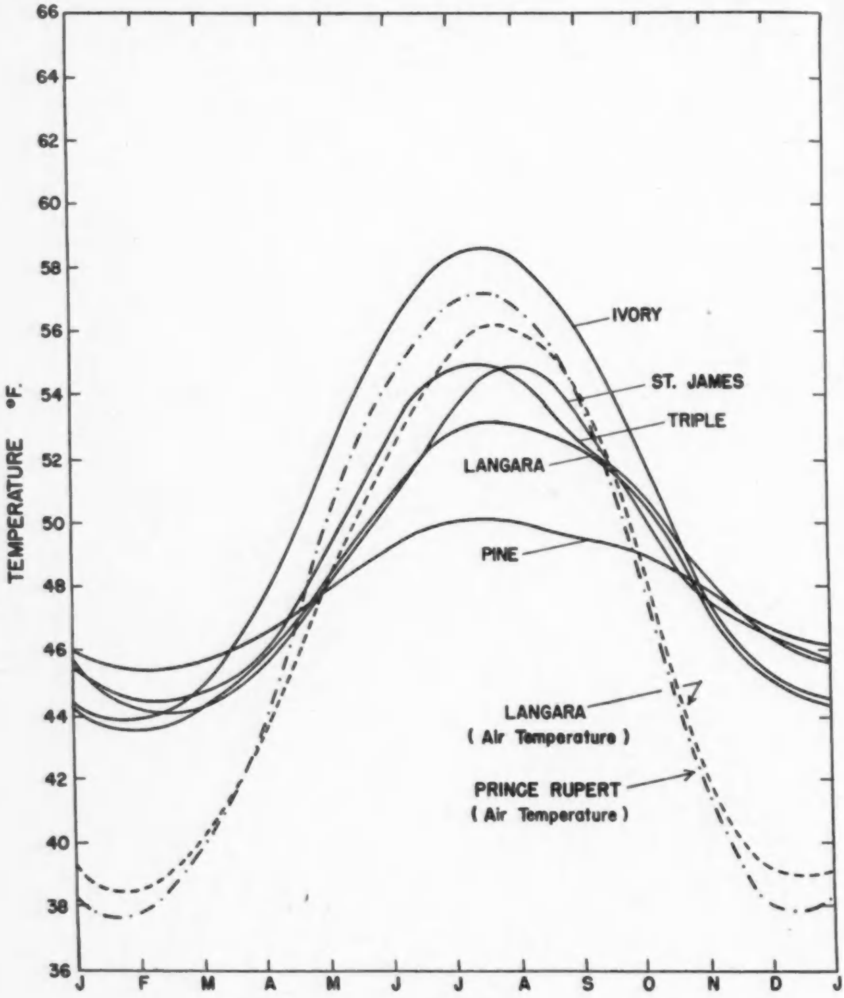


FIGURE 2. Mean monthly sea and air temperatures in the northern area.

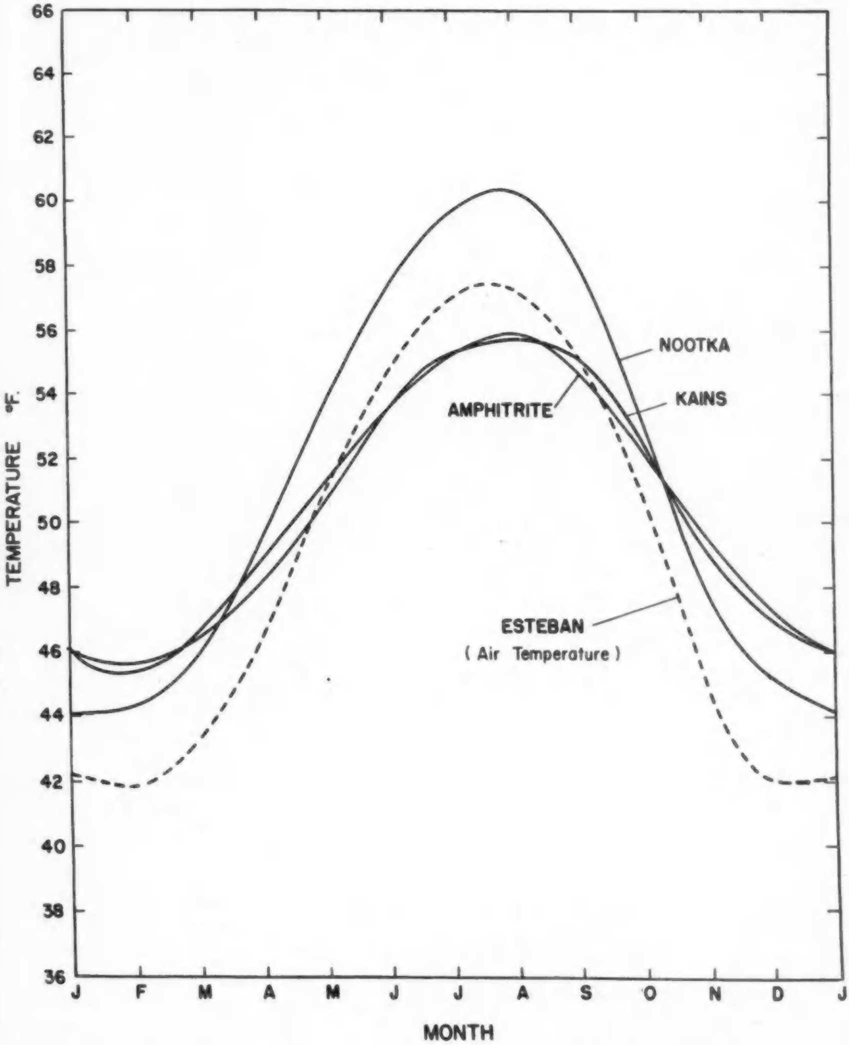


FIGURE 3. Mean monthly sea and air temperatures on the west coast of Vancouver Island.

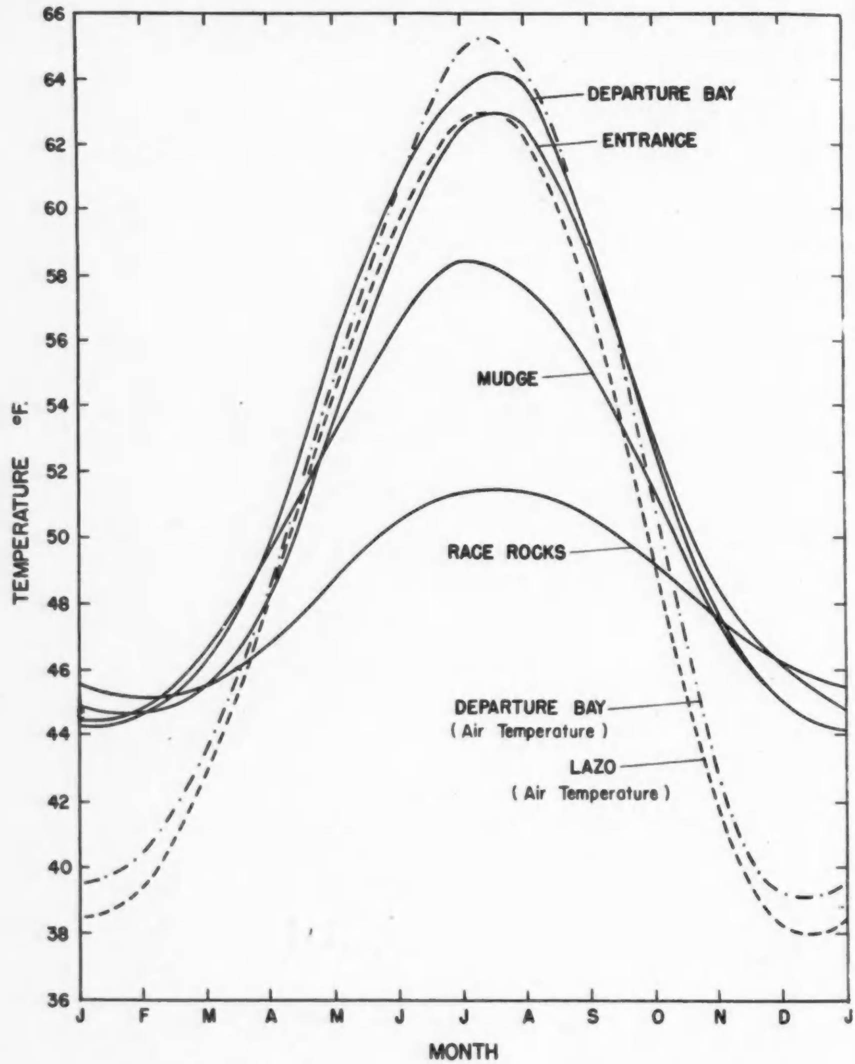


FIGURE 4. Mean monthly sea and air temperatures in the Georgia Strait area.

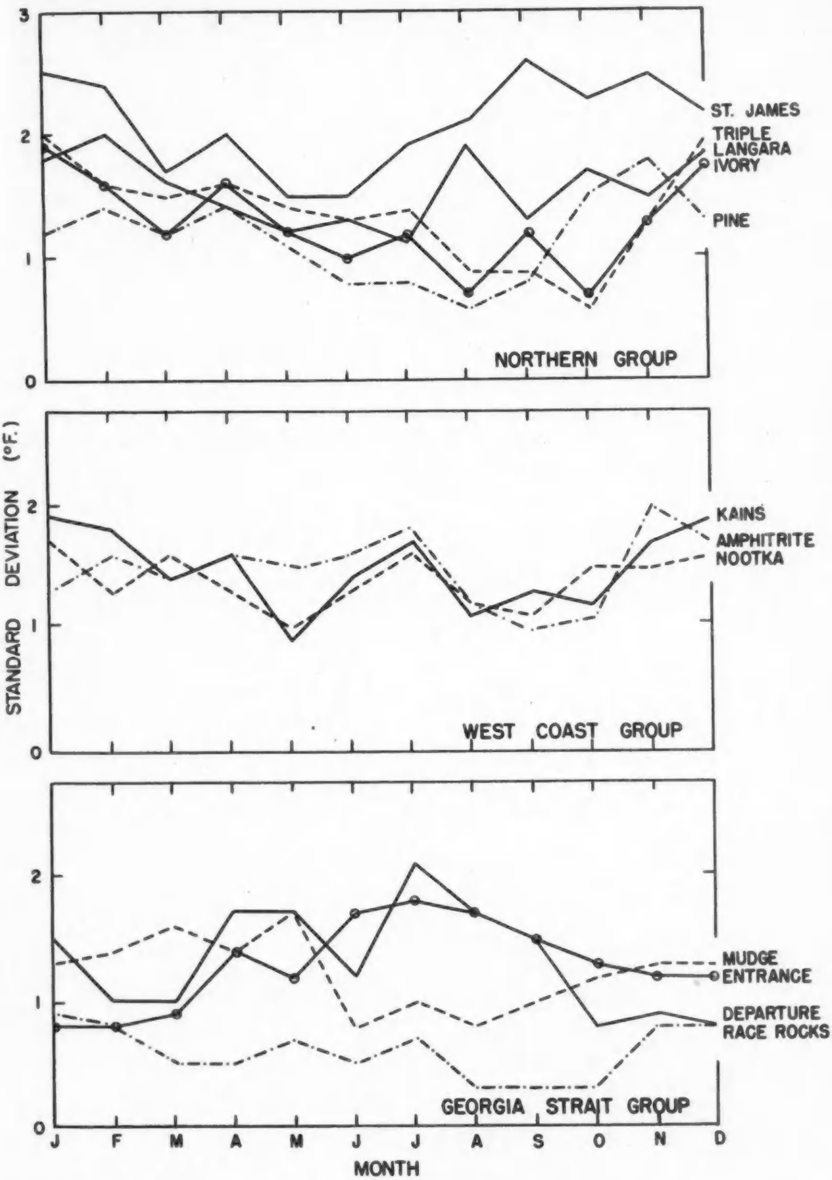


FIGURE 5. Standard deviations of monthly mean temperatures about grand monthly means.

the data of Figures 2–4. To reduce congestion the standard deviations for the stations have been plotted in three groups, the geographical grouping used in the earlier figures being retained. The smallness of the values indicates, by application of the Student "t" test, that the annual range of temperature is very significant. Accordingly the curves of Figures 2–4 may be regarded as typical for the respective stations.

It will be seen that except for Race Rocks and St. James the mean values of the standard deviations are closely grouped between 1.2 and 1.6 F.° (0.7 to 0.9C.°) and do not bear any direct relationship to the annual range of temperature at the individual stations.

## Correlation of Temperature between Stations

To determine whether or not these fluctuations in temperature were of the same relative magnitude, and in the same sense, for all the stations for any one year, the correlation coefficients between the temperatures at several pairs of stations were calculated. The temperature data were first examined within each geographical group by determining the correlation coefficients between the temperature at a selected comparison station and that at the remainder in turn. Ivory was then selected as comparison station for the whole coast, and the correlation coefficients between the temperature there and at all the other stations in turn were calculated. The results are given in Tables I and II.

Table I indicates that the year-to-year fluctuations in temperature discussed in the preceding section were in the same sense and of about the same relative extent for all the stations in the Northern and in the West Coast groups, but that the fluctuations for the Georgia Strait group were less regular. The correlation between the temperatures at Ivory and at Nootka in Table II indicates that for the Northern and West Coast stations taken as a group the year-to-year variations were of the same character, while the correlations between the temperatures

Table I. Correlation coefficients for monthly mean sea temperatures between stations by groups.

| | Correlations between | Jan. | Apr. | Jul. | Oct. |
|---|---|---|---|---|---|
| Northern Group | Ivory and | | | | |
| | Langara | .97 | .67 | .69 | .28 |
| | Triple | .97 | .73 | .91 | .39 |
| | St. James | .99 | .43 | .79 | .58 |
| | Pine | .92 | .98 | .78 | .74 |
| West Coast Group | Nootka and | | | | |
| | Kains | .73 | .79 | .84 | .79 |
| | Amphitrite | .63 | .85 | .93 | .80 |
| Georgia Strait Group | Entrance and | | | | |
| | Cape Mudge | .34 | .56 | —.30 | .68 |
| | Departure Bay | .28 | .54 | .62 | .83 |
| | Race Rocks | .65 | .82 | —.01 | —.21 |

TABLE II. Correlation coefficients for grand monthly mean sea temperatures for all stations relative to Ivory Island.

| Correlations between Ivory and | Jan. | Apr. | Jul. | Oct. |
|---|---|---|---|---|
| Langara | .97 | .67 | .69 | .28 |
| Triple | .97 | .73 | .91 | .39 |
| St. James | .99 | .43 | .79 | .58 |
| Pine | .92 | .98 | .78 | .74 |
| Kains | .93 | .97 | .75 | .74 |
| Nootka | .94 | .98 | .80 | .64 |
| Amphitrite | .84 | .87 | .84 | .77 |
| Mudge | .96 | .95 | —.02 | .71 |
| Departure Bay | .93 | .92 | .72 | .86 |
| Entrance | .35 | .92 | .75 | .54 |
| Race Rocks | .77 | .52 | .38 | .46 |

at Ivory and Entrance were lower in value and indicate a somewhat less systematic behaviour for the Georgia Strait group.

It is obvious that there will be differences in the rates of heating and cooling, which probably explains the variation of the correlation coefficients in April and October. Although the summer maximum generally occurs in August there is considerable variation from station to station within the calendar month which is not reflected in this analysis. When the maximum occurs in July, as at Mudge, a negative correlation results because of the arbitrary monthly grouping of the data.

However from the data in Table II it is concluded that from year to year the surface sea-water temperatures over the whole of the B.C. coast tend to deviate from the long-period mean in much the same manner.

## Harmonic Analysis of the Temperature Fluctuations

The regularity of the temperature curves of Figures 2–4 suggested that it might be possible to represent them by a simple harmonic formula. It was found that the temperature could be represented by the first terms of a Fourier series:

$$\begin{aligned} T(X) = {} & A_0 + A_1 \cos X + A_2 \cos 2X \\ & + B_1 \sin X + B_2 \sin 2X \end{aligned}$$

where $T(X)$ is the temperature in °F. and $X$ is a phase angle taken as 0° for January, 30° for February, etc. to 330° for December. The coefficients $A_0$, $A_1$, $B_1$ etc. were evaluated and are given in Table III. The actual temperature curves are reproduced in most cases within 0.5 F.° (0.3 C.°) by the series with five terms as above. Even closer agreement may be obtained by adding terms in 3X but it is doubtful if the additional terms are significant in view of the magnitude of the year-to-year fluctuations.

There is no immediately obvious physical significance in the simplicity of the series representing the temperature curves but it may be convenient for mathematical development to be able to represent the temperature changes in such a manner.

TABLE III. Fourier coefficients for representation of annual variation of surface sea-water temperature in degrees Fahrenheit, in the form

$$T(X) = A_0 + (A_1\cos X + B_1\sin X) + (A_2\cos 2X + B_2\sin 2X).$$

(N.B. Values calculated from formula and coefficients given are to be rounded off to the nearest 0.1°.)

| Station | $A_0$ | $A_1$ | $B_1$ | $A_2$ | $B_2$ |
|---|---|---|---|---|---|
| Langara | 48.00° | —4.32° | —2.50° | .18° | .35° |
| Triple | 49.03 | —4.43 | —2.44 | .93 | 0 |
| St. James | 48.54 | —4.10 | —2.82 | .80 | .68 |
| Ivory | 50.50 | —7.18 | —2.32 | .75 | .38 |
| Pine | 47.72 | —1.97 | —1.33 | .10 | —.15 |
| Kains | 50.47 | —4.82 | —2.17 | .23 | .30 |
| Nootka | 51.60 | —8.15 | —1.93 | .38 | .73 |
| Amphitrite | 50.58 | —4.62 | —1.95 | —.05 | .13 |
| Mudge | 50.90 | —7.10 | —0.90 | .50 | .20 |
| Departure Bay | 52.81 | —9.90 | —1.82 | 1.30 | .63 |
| Entrance | 52.29 | —9.03 | —2.62 | 1.55 | .58 |
| Race Rocks | 48.28 | —2.97 | —1.28 | .13 | 0 |

## CORRELATION BETWEEN SEA AND AIR TEMPERATURES

A comparison was made between the surface sea-water temperature and the air temperature. Since meteorological data were not obtained at all the light stations it was not possible to make direct comparisons. Instead, meteorological data for 1938–48 were obtained from the Monthly Records, Meteorological Division, Department of Transport for available stations which appeared to be representative of each of the three areas, and a comparison was made with these. The air-temperature stations selected were:

| | | |
|---|---|---|
| Northern Area | : | Langara and Prince Rupert |
| West Coast Area | : | Esteban |
| Georgia Strait Area | : | Departure Bay and Lazo |

The means of the daily maximum, and of the daily minimum temperatures were calculated for each month and the mean of these two taken as the mean temperature for the month. Grand monthly means were then calculated to indicate the general trend of the air temperatures for comparison with the water temperatures. The grand monthly mean air-temperature curves are plotted in Figures 2, 3 and 4 and are shown to be in complete phase agreement with those for the sea, although the amplitudes of the air-temperature curves are generally the greater. The higher temperature of the sea during the winter causes heat to be transferred from sea to air by conduction and evaporation and, under some circumstances, radiation. The consequent moderation of coastal winter climates is well known.

The deviations of the sea temperatures from the mean have been compared with the deviations of the air temperatures from their mean by calculating the correlation coefficients between these two quantities for each of the stations. The

results are given in Table IV, and show that there is in general good agreement between the two. It must be emphasized that this does not necessarily imply that departures from the mean air temperature are the cause of the sea-temperature departures.

TABLE IV. Mean correlation coefficients between monthly mean air and sea temperatures from 1938 to 1948. (The figures in brackets for St. James are obtained when readings for 1940 are omitted, suggesting possible instrument error this year.)

| | Air temp. | Sea temp. | Jan. | Apr. | Jul. | Oct. |
|---|---|---|---|---|---|---|
| Northern | Langara | Langara | .92 | .86 | .62 | .72 |
| Group | | St. James | .26 | .15 | .63 | .52 |
| | | | (.84) | (.53) | | |
| | | Triple | .90 | .82 | .92 | .05 |
| | | Ivory | .70 | .84 | .24 | .69 |
| | | Pine | .81 | .72 | .74 | .38 |
| West | Esteban | Kains | .88 | .75 | .91 | .92 |
| Coast Group | | Nootka | .66 | .77 | .89 | .89 |
| | | Amphitrite | .91 | .88 | .89 | .88 |
| Georgia | Lazo | Mudge | .28 | .88 | —.35 | .81 |
| Strait Group | | Entrance | .15 | .67 | .73 | .70 |
| | | Departure Bay | .75 | .95 | .76 | .85 |
| | | Race Rocks | .79 | .70 | .32 | .43 |

## FURTHER COMMENTS ON THE TEMPERATURE CYCLES

WEST COAST GROUP. It is suggested that the primary influence among this group is the upwelling which is known to occur during the summer in this region. The prevailing wind at this time is directed to the southeast, that is, parallel to the coast, and the resulting stress on the water surface causes a net mass transport of water in the upper layers in a direction to the right of the wind, that is, offshore (Tully, 1937b). This wind-transported water is replaced by colder water upwelling from depths not exceeding 600-900 feet (200-300 meters) (Sverdrup, 1938) and it is this which limits the maximum temperature attained in the region. The temperature curves for Kains and for Amphitrite are almost identical and are representative of the water on the open coast. The maximum temperature at Nootka is 4.5 F.° (2.5 C.°) higher, probably because the sampling station is in a more sheltered location, in Friendly Cove (Hollister, 1951), than are those of the other two stations. The data for Nootka may therefore be of most value as typical of conditions in a bay rather than in the open sea.

It is possible also that the stability associated with marked salinity gradients may be a factor in increasing the temperature range at an individual station. In this connection it may be remarked that in discussing the salinity distribution on the West Coast it is suggested later that the larger rise in salinity at Nootka than at the other two stations is a result of the concentration of the fresh water in the upper layers (Tully, 1937a). This increases the stability of the water and thereby reduces the vertical mixing with cooler water, and leads to a larger temperature rise in the surface water.

The transport of warmed water offshore in the summer and the continued upwelling of cool water should result in an appreciable temperature gradient normal to the Vancouver Island shoreline, with the temperature increasing seaward. Offshore surveys conducted by the Pacific Oceanographic Group show such an increase in temperature (Tully, 1937b; Doe, 1951) and this fact must be borne in mind when considering the lighthouse data.

GEORGIA STRAIT GROUP. The stations in this group are sheltered from the direct influence of the ocean and the change of temperature with season is likely to be determined chiefly by the change in insolation.

The water at Departure Bay attains the highest mean temperature for any of the stations, probably because it is in a very sheltered location in a shallow bay of 120 feet (37 meters) average depth.

The neighbouring station of Entrance where the water temperatures are generally about one degree lower than at Departure Bay may be regarded as typical of the exposed waters of Georgia Strait. The higher summer temperatures here and at Departure Bay compared with those at Kains and Amphitrite which are at approximately the same latitude are the result of the lack of upwelling, and of the shelter from the wind and consequent reduction in the wave-induced mixing of the upper water layer.

The Mudge station is located inside the entrance to Discovery Passage which leads into Johnstone Strait, the northern link with the ocean, and the maximum temperature here is 5 F.° (2.8 C.°) less than at Entrance. The tide floods southward, while the ebb which is stronger flows northward. Consequently the Georgia Strait water possesses a net motion to the north upon which is superimposed the tidal oscillation. The sea-water observations are made near the time of high tide when the flow is southward (flood), wherefor the data represent Georgia Strait water which has ebbed and flowed at least once. There are data to show that these waters are mixed to homogeneity through the whole depth of the channel (180 feet, 55 meters). Therefore it is concluded that the observations at Mudge represent the average properties of the upper 180 feet of Georgia Strait water, which may be expected to be less variable than the surface water observed at 3 feet (1 meter) depth at Entrance.

The annual range of temperature at Race Rocks is the second smallest of those at any of the stations. This undoubtedly results from its location in a region of considerable turbulence. The water coming from seaward undergoes appreciable mixing in the strong tidal streams of Juan de Fuca Strait, while the surface water from Georgia Strait, which might be expected to contribute to an increase in temperature, is in fact thoroughly mixed with the deeper cold water through 600 feet (180 meters) of depth during its passage through the San Juan Archipelago (Tully, 1942). This station provides one of the more extreme instances of the moderation of surface temperature by vertical mixing associated with turbulence.

NORTHERN GROUP. The maximum temperatures at St. James, Triple and Langara are 1 to 3 F.° (0.5 to 1.6 C.°) lower than those on the West Coast of Vancouver Island, and it is possible that this is partly due to the difference in

insolation between these groups whose stations are in comparable exposures. The difference in insolation due to change of latitude between the most southerly (Amphitrite) and most northerly (Langara) stations on the coast is only 8 per cent which can account only in part for the difference in maximum temperatures; in particular the difference between St. James and Langara is greater than could be accounted for by the latitude difference alone. The higher maximum at Ivory is the result of its more sheltered location and its temperature cycle may be expected to be typical of the waters of the inland passages in northern British Columbia. It is not easy to account for the small range of temperature at Pine (only 5½ F.°, 3 C.°). This station, from its intermediate latitude, might be expected to have an intermediate mean temperature, whereas it has the lowest for any of the stations. Lacking detailed information on the nature of the currents and circulation in this vicinity, it is presumed, from the small annual range of temperature (and of salinity), that the upper coastal waters are mixed with deeper ocean water at all seasons.

OVER-ALL ASSESSMENT OF THE TEMPERATURE CYCLES. To summarize the above discussion, we can select Kains or Amphitrite as equally representative of the Vancouver Island Pacific Coast, St. James as representative of the middle region and Langara as representative of the extreme north, with Nootka as possibly representative of the bays or inlets in the West Coast. Race Rocks, Mudge, and Pine are typical of regions of much turbulence, while conditions in the body of Georgia Strait may be best represented by those at Entrance.

In general the surface sea-water temperatures on the British Columbia coast may be regarded as at a sensibly uniform annual temperature minimum of 45°F. ± 1° (7.2°C. ± 0.5°) in February, rising in August to widely distributed maxima (50° – 64°F., 10° – 18°C.).

### Annual Variation of Surface Salinity

The monthly and grand monthly mean salinities were calculated for the twelve stations, and smoothed curves through the values are plotted in Figure 6. It is evident that the stations fall into three distinct groups:

(1) Salinity increasing to a maximum in the summer (Amphitrite, Kains and Nootka).

(2) Salinity decreasing to a minimum in the summer (Triple, Ivory, Mudge, Departure Bay and Entrance).

(3) Salinity substantially constant throughout the year (Langara, St. James, Pine and Race Rocks).

The same cause (insolation) is responsible directly or indirectly for both temperature and salinity changes. In some localities the two may be closely correlated (for example, absorption or solar energy may both raise the temperature of the water and, by increasing the evaporation, increase the salinity at the same time). However, the temperature and salinity changes, although correlated in time, may in other cases be of different character and, in fact, the similarity between the temperature cycles contrasts markedly with the three distinct classes

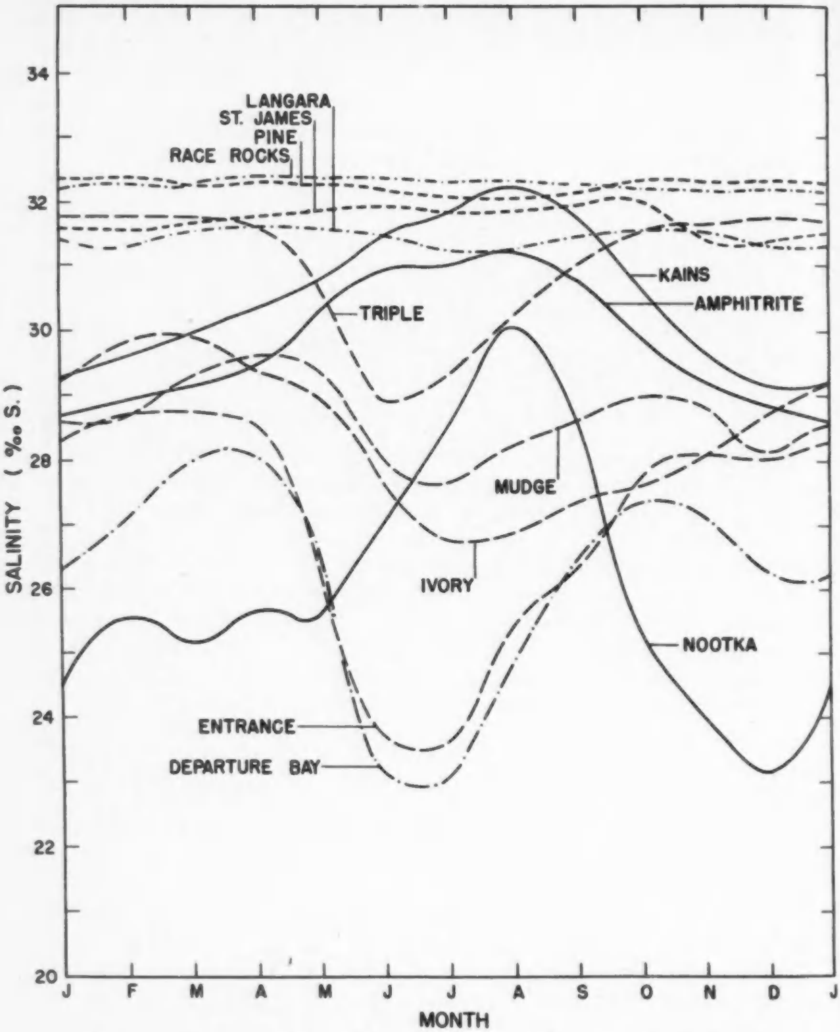


FIGURE 6. Mean monthly salinity at stations on the British Columbia coast.

of salinity cycle just mentioned. For instance, this independence in behaviour can occur because the addition of fresh water (for example, from a river) to sea water, while inevitably causing a change in salinity, may effect none in temperature if the two waters happen to have the same temperature before mixing, although such a circumstance in this area would be fortuitous.

Before discussing the salinity changes at the various stations, the difference

in the character of the run-off of fresh water from the mainland rivers and from the rivers on Vancouver Island and the Queen Charlotte Islands must be mentioned. The larger mainland rivers are fed by streams from the high mountains where the heavy winter precipitation is stored in glaciers and snow-fields, and their run-off reaches a maximum in June following the maximum rate of melting. On the other hand the rivers of Vancouver Island and the Queen Charlotte Islands respond directly to precipitation because they are fed by streams from lower mountains where storage in the form of snow does not occur to any great extent. (See also, Tully, 1938.) Some stations such as Langara and St. James are remote from rivers and are not subject to these influences.

STATIONS WITH SUMMER SALINITY MAXIMA

These are the three stations, Amphitrite, Nootka, and Kains, on the West Coast of Vancouver Island, and the changes in salinity between winter and summer are found to be statistically significant. The increase in salinity in the summer was at first attributed entirely to upwelling of more saline water, but further consideration suggested that another factor, the variation in precipitation during the year, might also be effective. Figure 7A shows the average precipitation during the year for the West Coast, and comparison with Figure 6 shows

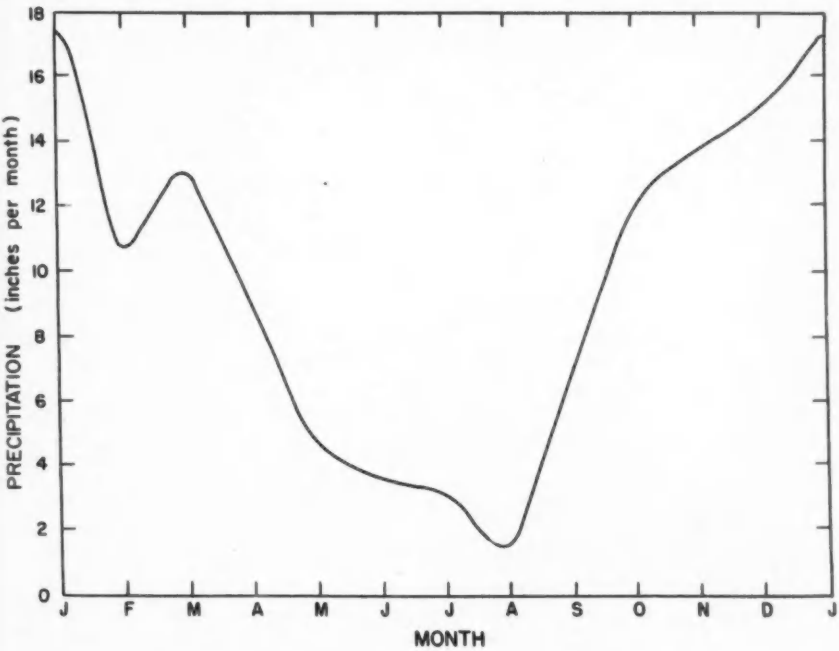


FIGURE 7A. Mean monthly precipitation on west coast of Vancouver Island for years 1941, 2, 4, 5 and 6.

that decrease in precipitation is accompanied by increase in salinity and vice versa. Since an increase in salinity in the neighbourhood of the coast could be attributed equally well to decrease in fresh-water run-off as to upwelling it seemed desirable to investigate the two processes further.

Since, as explained above, the transport of surface water occurs in a direction to the right of the wind, an indication of the extent of upwelling to be expected may be obtained from the occurrence and magnitude of the component of the wind directed to the southeast at the coast. This quantity, obtained from the Monthly Records of the Meteorological Division, is plotted in Figure 7B. It will be noted

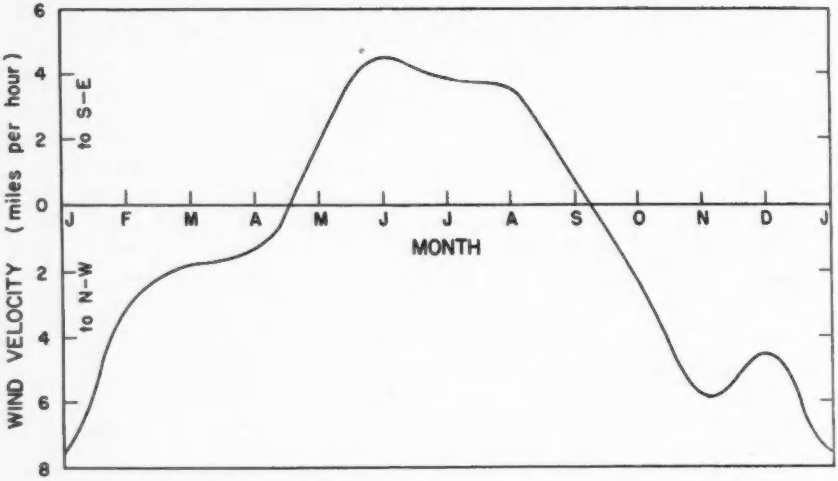


FIGURE 7B. Mean monthly wind-speed component parallel to west coast of Vancouver Island for years 1941, 2, 4, 5 and 6.

from Figures 6 and 7B that, although the wind has a southeast component only from mid-April to mid-September, yet the salinity commences to increase in January and to decrease in August. The fact that the average precipitation figures show a decrease from January to August, and thereafter an increase, suggests that precipitation may exert a major influence on the salinity, the changes of salinity following closely on changes in precipitation for the reasons already mentioned.

To determine the relative importance of upwelling and precipitation in controlling the salinity, the relation in Figure 8 was plotted, in which the points indicate the corresponding mean values of salinity and precipitation for each month. If these points are joined consecutively the resulting line shows a sharp increase in salinity from May to June (just after the southeasterly directed wind commences), and a decrease after September or October (just after this wind has ceased). Since the upwelling process involves the movement of considerable masses of water, it is only to be expected that there will be some lag between the change of the wind and the establishment or cessation of significant upwelling.

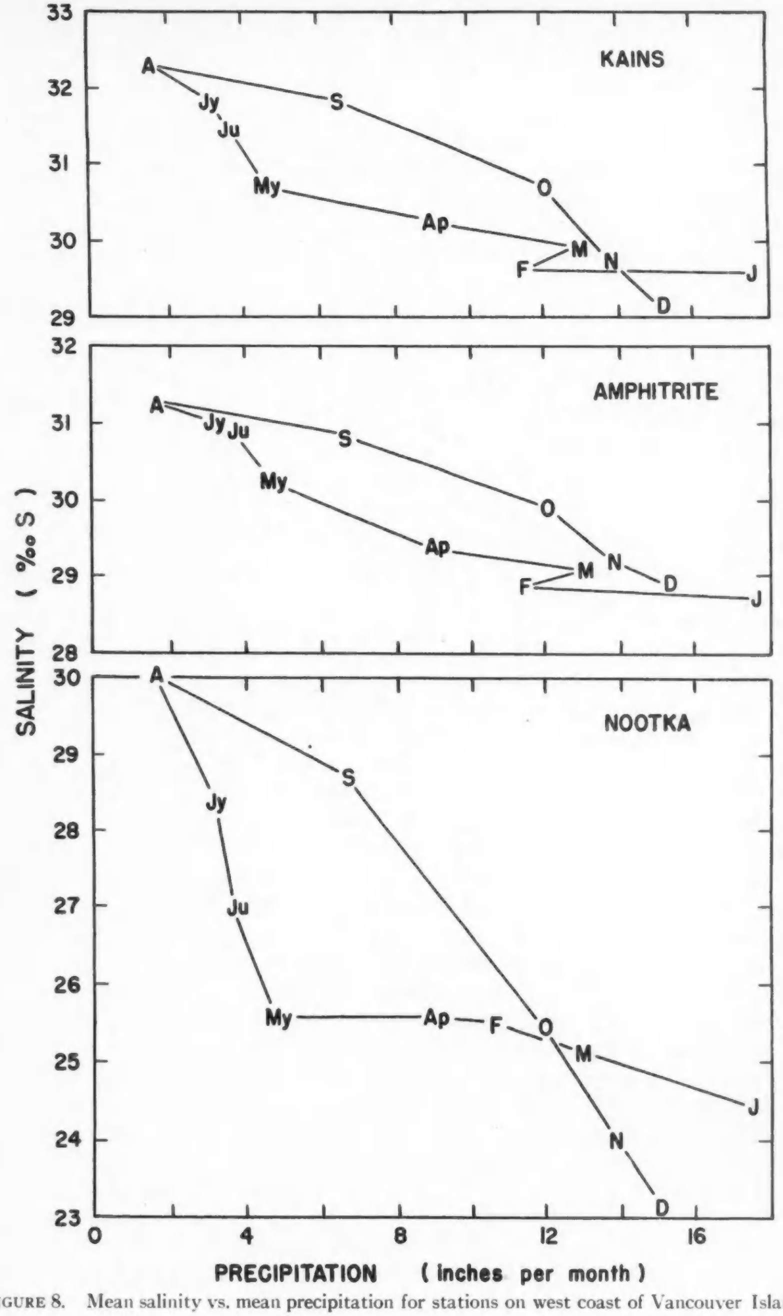


FIGURE 8. Mean salinity vs. mean precipitation for stations on west coast of Vancouver Island.

It is possible that a careful study of the correlations between wind, precipitation and sea temperature in detail for individual years would yield valuable information on the rate of development and of decay of the mass transport of the surface waters due to the wind stress.

A point which requires explanation is that while the change of salinity ascribed to precipitation and that ascribed to upwelling respectively are the same at Kains as at Amphitrite, the changes at Nootka are appreciably greater. At Nootka the maximum salinity is 1 to 2 $^0/_{00}$ less than at the other two stations but the minimum is 6 $^0/_{00}$ less. The difference may arise wholly, or in part, from the fact that the positions where the water samples are taken at Kains and at Amphitrite (Hollister, 1951) are on the open coast exposed to the ocean swell, while the samples at Nootka are taken in Friendly Cove in a more sheltered location which is less subject to waves and where the fresh water is still concentrated in the upper layers giving a low surface salinity (Tully, 1937a). It is also possible that local inequalities in rainfall (common on the B.C. coast) might play some part in explaining the increased slope of the precipitation-controlled part of the salinity change. These factors, however, should not affect the increase due to upwelling.

A simple formula may be devised for each station to describe the mean salinity changes, using the precipitation and wind speed as variables, but it is doubtful if such an empirical formula has any fundamental significance. The essential feature to be recognized is that both precipitation and upwelling contribute to the determination of the salinity change. It is probable that an analysis of the data day by day would yield a better quantitative understanding of the part played by the two processes, and determine the reason for the difference between Nootka and the other stations.

### STATIONS WITH SUMMER SALINITY MINIMA

The summer minima in salinity exhibited by the stations Triple, Ivory, Mudge, Entrance, and Departure, along the mainland coast are undoubtedly due to the river discharges during this period. Triple is influenced by the Skeena River, Ivory by the Dean and Bella Coola Rivers, and the stations in Georgia Strait by the Fraser River.

The average monthly discharge of the Fraser River rises from a minimum of $0.8 \times 10^{11}$ cubic feet ($2.2 \times 10^9$ cubic meters) in March to a maximum of $9 \times 10^{11}$ cubic feet ($26 \times 10^9$ cubic meters) in late May, whereas the salinities at Entrance and Departure commence to fall in early April and reach minima in mid-June. The time lag is due to the interval required for the fresher water to reach these stations after circulating in Georgia Strait. The further delay in arrival at Cape Mudge indicates the longer time required for the Fraser River water to reach this more distant station. The annual range of salinity here is reduced because the waters in 180 feet (55 meters) of depth are mixed to homogeneity in Discovery Passage. This corresponds to the reduction of the temperature variation discussed previously in connection with the Georgia Strait stations.

The Fraser and Skeena River waters which cause the salinity minima at the

the widely separated regions of Entrance and Triple stations come largely from snow-melt in substantially the same inland region. Therefore these salinity minima occur at the same time and follow closely the maximum river discharge. The less marked change at Ivory is presumed to be due to the smaller stored run-off in this region, that from the Dean and Bella Coola Rivers combined being about 10 per cent of that of the Fraser River.

#### STATIONS WITH SMALL ANNUAL RANGE OF SALINITY

Langara and St. James are remote from appreciable sources of fresh water and consequently little change in salinity during the year is observed or expected.

The small annual change in salinity at Mudge and Race Rocks is due to the mixing of the surface and deep waters in the turbulent passages as was discussed earlier in connection with the temperature cycles. Mudge is the less saline and more variable of these two because it is dominated by the upper 180 feet (55 meters) of Georgia Strait discharge, whereas at Race Rocks the depth of mixing is of the order of 600 feet (180 meters), and is affected by the intrusion of upwelled ocean water into Juan de Fuca Strait (Tully, 1942).

The constancy of the temperature and salinity at Pine presumably results from the vertical mixing due to the tidal currents and winds in the region of Queen Charlotte Sound.

### Climatic Grouping

These temperature and salinity cycles may be regarded as climatic indices corresponding to the temperature and precipitation cycles in the atmosphere. In this sense there are three climatic regions, which are defined in terms of the salinity cycles, since the temperature cycles are similar over the whole coast. At positions far removed from the influence of rivers, oceanic conditions prevail; there is a moderate range of temperature change from winter to summer, but little or no variation of salinity. Along the coast, where the surface salinity is dominated by *run-off* from rivers draining the regions of snow storage, the salinity tends to be lowest in early summer. Along the ocean coast of Vancouver Island, and probably the bays and inlets of the Queen Charlotte Islands, where the winter and summer rainfall *runs off directly*, the salinity tends to be lowest in the winter.

In each of these regions there are three type-locations which modify the climatic cycle. The effects of heating and dilution are conserved at the surface in *harbours* and *bays* where the wind effects are small, and the variations are maximum. In open *seaways* where the wind stirs the water the variations are less but extend to appreciable depths. In *passes*, *narrows*, and seaways having turbulent tidal currents, the waters are mixed to homogeneity throughout the depth, so that the seasonal variations are reduced.

In Table V the stations are arranged according to this plan, which appears to provide a more acceptable grouping than the purely geographic or salinity classifications.

Mudge is grouped with Race Rocks because they both represent regions of total mixing, although the former includes about 180 feet (55 meters) of depth

TABLE V. Classification of Daily Sea-Water Observation Stations according to climatological region and type location.

| | Region | | |
|---|---|---|---|
| | Oceanic | Coastal | |
| | No run-off | Direct run-off | Stored run-off |
| Harbours and bays | — | Nootka | Departure Bay |
| Coastal seas | Langara<br>St. James | Kains<br>Amphitrite | Entrance<br>Ivory<br>Triple |
| Straits, turbulent seaways | Pine | — | Race Rocks<br>Mudge |

and the latter includes about 600 feet (180 meters). Pine evidently respresents oceanic water, subject to upwelling and mechanical mixing from the tidal currents in the vicinity. The small annual change at these stations suggests that the salinity here could be taken as a measure of the prevailing salinity of oceanic water from which the dilution by fresh water at the coastal stations could be determined.

The grouping of the remaining stations is evident, both from geographical and salinity considerations.

## CONCLUSIONS

The annual temperature cycle is similar at all stations, with minima (45°F. ± 1°) (7.2°C. ± 0.5°) occurring in February and maxima in August. The annual range of temperature varies from 5 F.° (2.8 C.°) at Race Rocks to 20 F.° (11C.°) at Departure Bay. The smallest annual ranges, at Race Rocks, Pine Island and Cape Mudge, are attributed to the effect of turbulent mixing with deep, cold water; the intermediate ranges at the West Coast stations exposed to the Pacific Ocean are associated with the upwelling of cold water due to the summer wind stress; whereas the largest annual ranges occur at the stations such as Departure Bay and Nootka which are sheltered from the open ocean and where the water is not subject to vertical mixing.

Three distinct salinity cycles are evident. The stations on the west coast of Vancouver Island exhibit salinity maxima in the summer due to the upwelling and to the seasonal decrease in precipitation. The stations on the mainland coast show a summer salinity minimum due to the diluting effect of the fresh-water run-off from the main rivers. There is scarcely any annual change in salinity at Cape St. James and Langara because they are far removed from the influence of big rivers, and at Pine Island and Race Rocks because the small amount of brackish surface water is mixed with such a considerable depth of saline water in the turbulent passages.

## ACKNOWLEDGEMENT

Acknowledgement is made for permission to use the "Observations of Sea Water" collected by the Pacific Oceanographic Group, Pacific Biological Station, Nanaimo, B.C., and to Dr. J. P. Tully, his staff of the Pacific Oceanographic Group and to Dr. W. M. Cameron for helpful discussion and criticism during the progress of the investigation.

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| Volume II | 1935–1937. | Volume VII | 1946–1947. |
| Volume III | 1938–1939. | Volume VIII | 1948. |
| Volume IV | 1940–1941. | Volume IX | 1949. |
| Volume V | 1942–1943. | Volume X | 1950. |

# The St. Lawrence Spring Run-Off and Summer Salinities in the Magdalen Shallows

By Louis Lauzier

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*(Received for publication May 6, 1952)*

The waters of the southwestern sector of the Gulf of St. Lawrence, known as the "Magdalen Shallows", are highly stratified during the spring and summer. The thickness and salinity of the surface layer reach a minimum during the summer (Lauzier and others, 1951). Fresh water flows over the sea water, mixing with it to form a well-defined surface layer. The difference of salinity between this and the lower zone is a measure of its dilution by land drainage.

Under these circumstances it is possible to calculate the volume of fresh water necessary to reduce the salinity of the surface layer to its summer minimum, which has varied, on the north coast of Prince Edward Island, between 25.2 ‰ in 1947 to 27.7 ‰ in 1949. It is also possible to calculate, from data supplied by the Water Resources Division, Department of Resources and Development, Ottawa, the volume of fresh water entering the area from the 360,000-square-mile drainage basin of the St. Lawrence system. Both these volumes have been calculated as layers of various thicknesses covering the western Gulf which has an area of about 26,000 square miles. The volume of the St. Lawrence run-off in April, May and June and the volume of fresh water needed to reduce the salinity of the surface layer from its June level to its minimum are compared in the table and the graph for the years 1945 to 1949. There is a lag of about three months between the maximum run-off of the St. Lawrence in the spring months and the minimum salinities.

Table I

| Year | Average run-off of St. Lawrence River April to June[a] | Thickness of a layer over southwestern Gulf of St. Lawrence equivalent to: St. Lawrence run-off May to June | Fresh water required to reduce salinity of surface layer to its minimum |
|---|---|---|---|
| | *1,000 cu. ft. per sec.* | *metres* | *metres* |
| 1945 | 445.7 | 1.48 | 1.12 |
| 1946 | 404.7 | 0.9 | 0.83 |
| 1947 | 608.8 | 2.02 | 1.68 |
| 1948 | 396.1 | 1.32 | 0.97 |
| 1949 | 426.9 | 1.42 | 1.02 |

[a]Data supplied by the Water Resources Division, Department of Resources and Development, Ottawa.



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A good correlation is indicated which suggests the excellent possibility of forecasting the salinity variations of the surface layer during the summer on the basis of the run-off from the St. Lawrence Basin, and also to a lesser degree of accuracy, the summer minimum salinity along the north coast of Prince Edward Island.

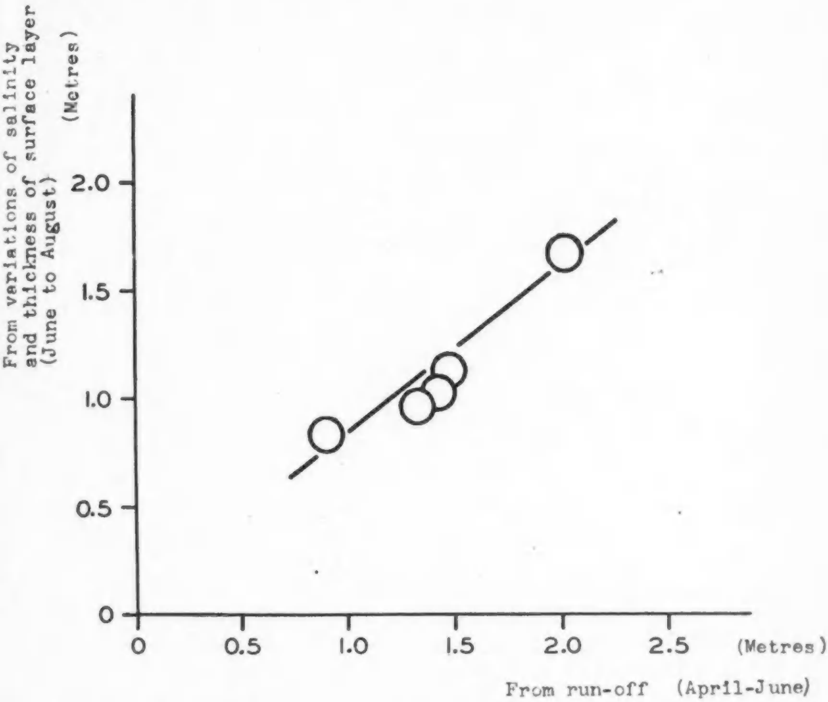


FIGURE 1. Thickness of fresh-water layers over southwestern Gulf of St. Lawrence equivalent to St. Lawrence run-off during the April-June period, as related to the thickness of a fresh-water layer sufficient to reduce the salinity of the surface layer from its June level to its minimum in August.

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# A Winter Incursion of Slope Water on the Scotian Shelf

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(*Received for publication June 6, 1952*)

## ABSTRACT

A sub-surface incursion of slope water, of temperatures as high as 12.0°C., over an area in the vicinity of the submarine channel entering the Scotian Gulf, took place in the winter of 1949. This is the first occasion on the Scotian Shelf where the slope water of such temperatures has been observed north of the edge of the continental shelf.

## INTRODUCTION

In the triangular area of the western North Atlantic outlined by Nova Scotia. Bermuda and Chesapeake Bay, the water subdivisions are designated (Iselin, 1936) as "coastal water", "slope water", "Gulf Stream", and "Sargasso Sea", Off the Nova Scotia coast, "coastal water" extends out to the edge of the continental shelf, and the band of "slope water" extending from the edge of the continental shelf to the northern edge of the "Gulf Stream" is approximately 170 miles in width.

In the winter months, the transition from "coastal water" to "slope water" is, off the Nova Scotia coast, very sharply defined by temperature changes, and in particular by the vertical tendency of the isotherms which establish very intensive horizontal temperature gradients.

In February, 1949, the water temperature conditions off the Scotian coast were assessed, in a bathythermographic survey, under the joint auspices of the Naval Research Establishment at Halifax, N.S., and the Atlantic Oceanographic Group.

## DATA

### The Bathythermographic Survey of February, 1949.

The details of the survey are shown in Figure 1. Lowerings of a bathythermograph (BT) were made at 142 points to furnish detailed information of the vertical distribution of temperature at each of these points.

The observations were initiated at point A and continued at half-hour intervals through points B, C, D, E and F. A storm then forced the ship to run



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offshore for approximately thirty hours, after which the observations were renewed at point F through points E, G, H and finishing at point I.

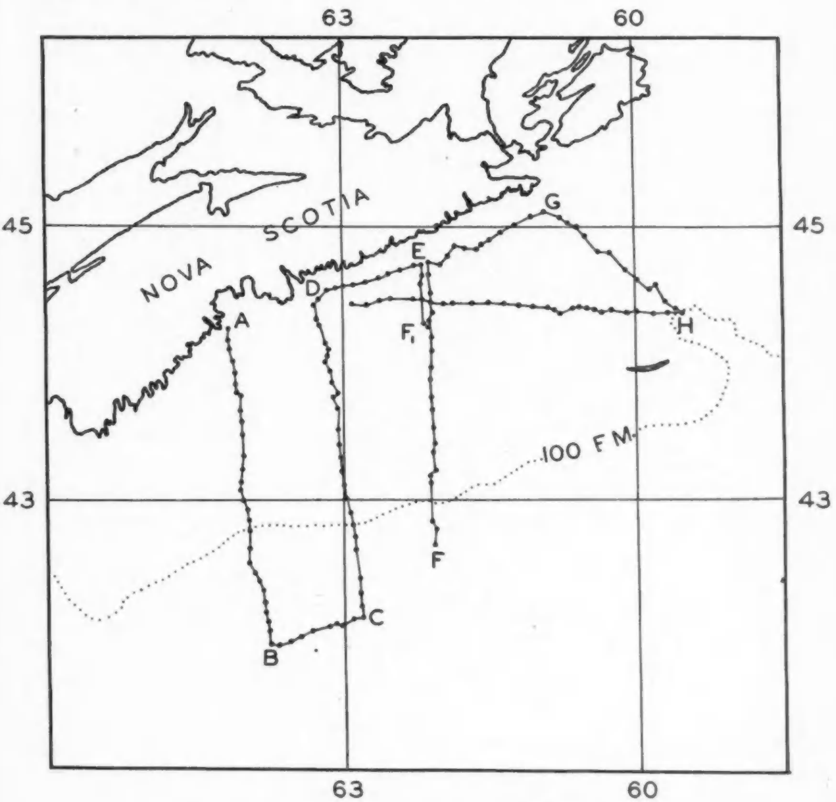


FIGURE 1. Details of BT observations in February, 1949.

## THE VERTICAL DISTRIBUTION OF TEMPERATURE IN SECTION AB.

The vertical distribution of temperature in the section AB is illustrated in Figure 2. Section AB extends from Lunenburg to cross La Have Bank and beyond the edge of the continental shelf. On the shelf the temperatures range from less than 2.0°C. to less than 6.0°C., the higher temperatures being on the bottom. Beyond the edge of the shelf and at a depth of 100 metres, within a distance of ten miles, the temperatures increase rapidly from 6.0° to 12.0°C. and greater. The sharp horizontal temperature gradient marks the northern edge of the "slope water".

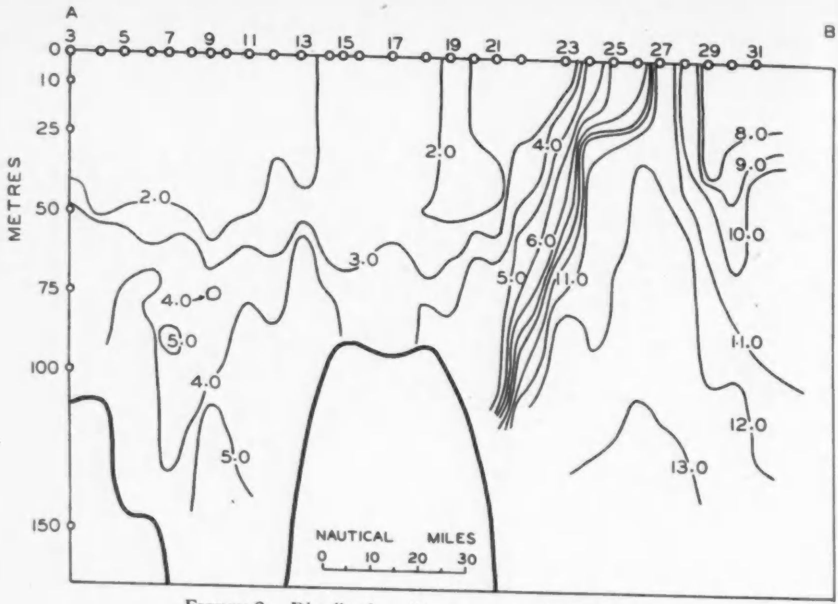


FIGURE 2. Distribution of temperatures in Section AB.

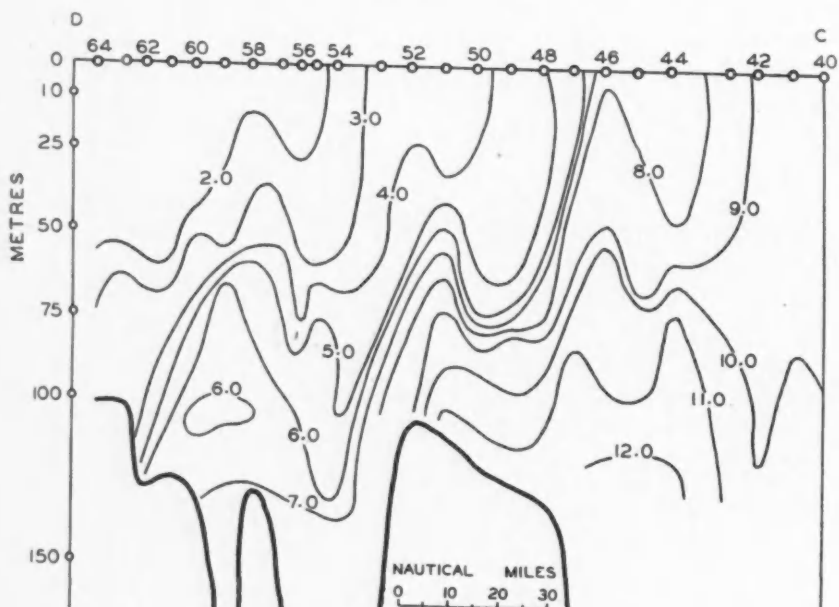


FIGURE 3. Distribution of temperatures in Section DC.

THE VERTICAL DISTRIBUTION OF TEMPERATURE IN SECTION DC.

The vertical distribution of temperature in the section DC is illustrated in Figure 3. Section DC extends from Halifax to the west of Emerald Bank and beyond the edge of the continental shelf. In this section an incursion of "slope water" has taken place, as shown by the presence of bottom waters of temperatures as high as 12.0°C. on the Scotian Shelf. The temperature of the main body of coastal water ranges from less than 2.0° to 7.0°C. The incursion of "slope water" has occurred chiefly at depths greater than 50 metres and the trend of the isotherms illustrate the northerly extension of the "slope water" below these depths.

The portion of the section involved and affected by this incursion of slope water is approximately thirty miles long, and the area affected might easily be as much as 1000 square miles.

THE VERTICAL DISTRIBUTION OF TEMPERATURE IN SECTION EF.

The vertical distribution of temperature in the section EF is illustrated in Figure 4. Section EF extends from Beaver Harbour past the western edge of Sable Island Bank and beyond the edge of the continental shelf. The temperatures of the coastal waters range from less than 1.0° to 8.0°C. Beyond the edge of the continental shelf a sharp horizontal temperature gradient is more pro-

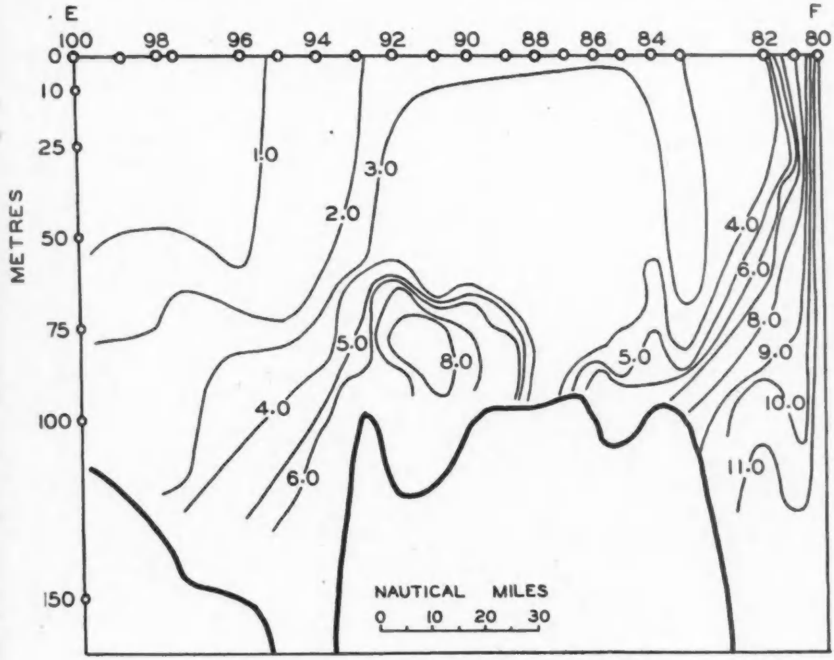


FIGURE 4. Distribution of temperatures in Section EF.

nounced in the surface layer where, over a distance of ten miles, the temperatures rapidly increase from 6.0°C. to greater than 11.0°C. There is some indication of the tendency of the warmer slope waters to extend northward over the edge of the continental shelf at depths of 100 metres. As the observations in this section were made following a storm (Hachey, 1935; Longard and Banks, 1952), there is reason for suspecting that the incursion of slope waters observed in section DC occurred also in section EF previous to the storm. In any event, differential water movements, as between the upper fifty metres of water and lower fifty metres, could readily cause a marked incursion of "slope water" in this section.

## DISCUSSION

The flooding of the continental shelf south of Nova Scotia by incursions of offshore waters has been observed in the past (Leim and Hachey, 1935), but only in the late summer months. At no time, in seasonal cruises of the shelf, have bottom-water temperatures been higher than 8.0°C. on the outer banks. Heretofore, most of our winter cruises have been limited to the Scotian shelf, with the exception that in 1936 a co-operative effort between the Woods Hole Oceanographic Institute and the Fisheries Research Board of Canada completed two sections extending from the Nova Scotia coast well beyond the edge of the continental shelf (Hachey, 1938). In these extended sections slope water temperatures greater than 7.0°C. were some distance south of the edge of the shelf. The observations of 1949 are therefore of considerable significance in that they record an incursion of waters of vastly different temperature characteristics than those considered normal to the Scotian Shelf. The implications to fishery problems, and marine biological problems generally, are obvious.

The submarine physiography of the Scotian Shelf (Hachey, 1937) is an important factor in confining the major effect of such incursions to the area that has been named the Scotian Gulf. The submarine channel of depths greater than 75 fathoms (136 m.) is located between La Have and Emerald Bank. This channel opens into the submarine Scotian Gulf which, with the exception of Sambro Bank, is of a depth greater than 75 fathoms (136 m.). Other than the Cansan Channel, which is limited in its penetration of the Shelf, this submarine channel opening into the Scotian Gulf is the only means through which slope water of depths of 50 fathoms (91 m.) or greater can be distributed on the Scotian Shelf. Hence it is to be expected that when incursions of offshore water take place, the distribution is related in part to the submarine physiography of the shelf.

## SUMMARY

1. An incursion of slope water on the Scotian Shelf was observed in the winter of 1949, and bottom-water temperatures were as high as 12.0°C.

2. As is to be expected, the incursion occurred in the vicinity of the submarine channel entering the Scotian Gulf, and at depths greater than 50 metres.

3. This is the first occasion on the Scotian Shelf where extensive observations have located the slope water of such temperatures well northward off the edge of the continental shelf.


## ACKNOWLEDGMENT

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